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THE OCEAN

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F. D. O.

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CHAPTER I

THE OCEAN BASIN

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We may look upon our physical world as made up of three elementary regions or spheres, each different from but intimately related to the other. First, there is the atmosphere, which is the benign mixture of gases which we breathe and which clothes the earth like a mantle. Secondly, there is the lithosphere—the zone of the rocks. It forms the crust of the earth, builds the continents, supports the ocean basins and makes up the dry land on which we live. Thirdly, there is the hydrosphere, the watery covering of the earth—the oceans and the seas.

Of these three regions the lithosphere is by far the largest. It may be said to extend down some fifty to seventy-five miles to the great core of the earth itself which we may perhaps count as a fourth region—the centrosphere. The character of this core we can only infer but cannot observe, and indeed we can only observe directly a very thin skin of the lithosphere itself. When we consider the movements of land masses and continents and those gigantic processes which have

built up the earth as we know it, we must remember always that we are dealing at the most with a layer about three miles thick. Yet the total diameter of the earth is 7,918 miles. If the earth were reduced to the size of an orange, the atmosphere would become no thicker relatively than the tissue paper wrapping round it. And if the earth were a ball four inches in diameter, all the oceans with their great depths would become a film one-thousandth of an inch thick. We should see it as a mere wetness clinging to the ball by capillary attraction. If the earth were one foot in diameter, about the size of a football, the oceans would be represented by a film one-two-hundredth of an inch thick and most of the land that forms the continents would become a shell less than one-thousandth of an inch thick on the surface of the football. Mt. Everest would be seen as a pimple less than one-hundredth of an inch in height.

There is a constant exchange of gases between the hydrosphere and the atmosphere and, on land, between living things and the atmosphere. Evaporation from the surface of the sea, and from all the wet surfaces of the earth, supplies the water vapour which is part of the atmosphere, variable from place to place, without which life on land could not exist. The water vapour picked up descends as rain, which, with the action of frost and wind, erodes the surface of the lithosphere, carrying down sediments to the streams and rivers. These are continually spreading new layers upon the sea bottom. The Thames carries to the sea between one and two million tons of sediments every year and it has been estimated that the British Isles are being worn away at the rate of one foot in three thousand years. From all the lithosphere about 3·7 cubic miles of waste material are

carried to the sea every year, enough to cover the land to a depth of 1,450 fathoms in about six and a quarter million years. But the lithosphere is always remade elsewhere. Seas recede and river mouths silt up. In past ages land has heaved itself above the surface of the sea. Animal and plant life, nourished and supported by the atmosphere and the lithosphere, dies and in decay passes into the soil.

The woods decay, the woods decay and fall.
The vapours weep their burthen to the ground.

So our world, old yet ever youthful, is constantly renewed. Yet during the history of the earth there have been changes in the relationship of the three spheres to one another. There is evidence that the ocean is larger now and contains more water than the seas in which the coal measures were laid down. Vast changes in the relative positions of land and water have occurred. Sedimentary rocks, now far inland in the centres of continents, were laid down in shallow seas and some of the theories which seek to account for observed geological facts require the foundering of whole continents beneath primeval oceans.

The oceans and seas of the world cover an area of about 140,000,000 square miles or about two-thirds of the earth's surface. They occupy a volume (324,000,000 cubic miles) fifteen times greater than that of the land above sea level (about 23,000,000 cubic miles) and fill a vast irregular depressed basin with an average depth (12,600 feet or 2,078 fathoms) more than five times the average height of the land which, in spite of the majestic height and extent of the great mountain systems, is only 2,300 feet. The greatest depth of the ocean, however, off

the coast of Japan, is not so much more than the greatest height of the land—34,818 feet (about six and a half miles) as against 29,002 feet (about five and a half miles) which is the height of Mt. Everest. If all the depressions

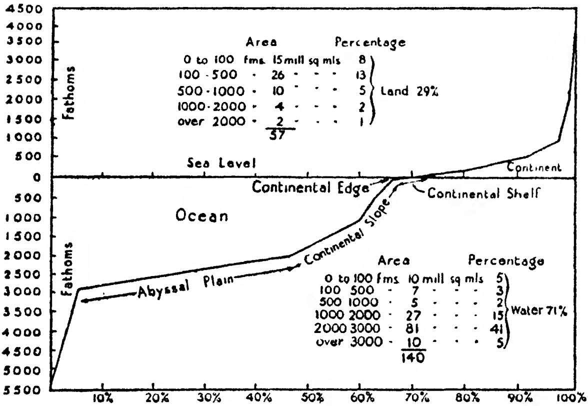

FIG. 1. Diagrammatic section showing the average contour of the lithosphere. Based upon the percentage of the areas between the contour lines above and below sea level.

of the ocean floor could be filled in by cutting away material from the continental elevations we should drown all the land beneath the surface of the sea to a depth of 1,700 fathoms. This is known as the 'mean sphere level'.

Around the continents below sea level a small proportion of the floor of the ocean basin forms a shallow platform of varying extent where the depth is less than 100 fathoms. This is the 'continental shelf' (Fig. 1). In places it is very wide and supports continental islands,

as, for example, off the north-west coast of Europe where it extends out westwards from Land's End for a distance of 200 miles embracing the British Isles and the whole of the North Sea. In other places the shelf is almost absent and the coastline plunges straight down with little interruption into deep water, as it does off the mountainous coast of western America. The continental shelf slopes very gently downwards with an average inclination of about 1 in 500 and is the area upon which the heavier materials washed down by the river and eroded from the shores are deposited. At a depth of about 100 fathoms is the 'continental edge' (Fig. 1), where the slope of the sea floor steepens to an average gradient of about 1 in 10 down to the mean sphere level. This steep slope occupies an area three times greater than that of the continental shelf. It is known as the 'continental slope' and is the region upon which the finer deposits from the land finally come to rest, the finest sands and muds raining down impalpably through deep, still water. Like the shelf it is very variable in extent in different parts of the world. The contour map (Plate I) shows what vast areas of the ocean floor around the land masses would be laid bare if the sea level were to subside 1,000 fathoms. Europe would be joined to Greenland and Australia to Asia. But off the west coast of America and around Africa, except for Madagascar, the continental shelf is comparatively narrow. At about the 2,000-fathom line the slope of the sea floor levels out and the greater part of it—about 60 per cent. of its whole area—lies between 2,000 and 3,000 fathoms. Here it forms a vast undulating plain—the 'abyssal plain'. All this part of the ocean floor lies beyond the reach of deposits washed down from the continents. It is covered by oozes which consist of

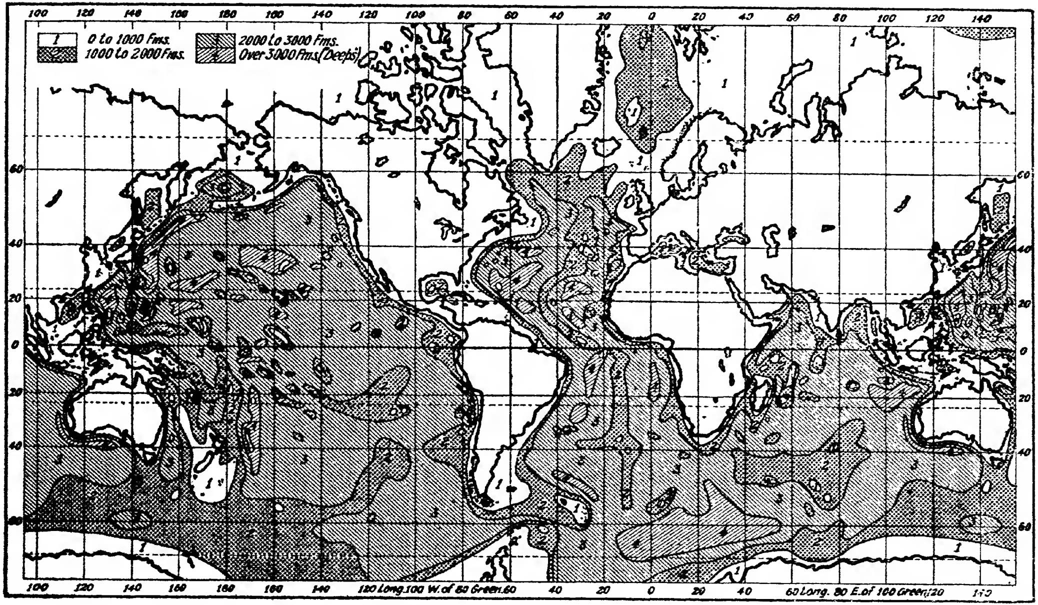

PLATE I. Ocean Bottom Contours.

the accumulated skeletons of floating animals and plants, microscopic but innumerable, with organic remains such as the ear bones of whales and materials of meteoric origin. All these have been settling down with inconceivable slowness almost since the first appearance of life in the waters. From the abyssal plain volcanic elevations project upwards comparatively steeply and break surface as oceanic islands, often capped with coral growths, as are Bermuda in the Atlantic, Christmas Island in the Indian Ocean and the many lovely islands of the Pacific.

Less than 2 per cent. of the sea floor lies at depths greater than 3,000 fathoms. Most of the deeps, as they are called, occupy elongated trenches often close to the coasts of the continents or on the margins of the ocean basins. There are several such trenches on the western side of the Pacific (Plate I), where the deepest water in the world occurs. This is the Japan Trench, just east of the Japanese Archipelago, where there is a depth of 5,800 fathoms (about six and a half miles). In the Mariana Trench, where the *Challenger* obtained her deepest sounding of 4,475 fathoms, a depth of 5,395 fathoms (a little over six miles) has now been recorded. There are many similar trenches in the Pacific, nearly all on the western side, but in the Atlantic they are comparatively rare. Such as there are lie on the western side of the ocean and the deepest water in the Atlantic occupies a trough immediately north of the island of Puerto Rico, where there is a depth of 4,812 fathoms. There is another with a depth of 4,545 fathoms immediately east of the South Sandwich Islands in nearly 60° South. It is noticeable that very many of these deeps take the form of steep-sided declivities close to, and often

parallel with, parts of the sea floor which rise steeply from great depths to the surface where they are crowned by chains of islands. The South Sandwich Deep, just mentioned, and the Japan and Mariana Trenches are typical in this respect and are, from their relationship to the submarine ridges and to the islands on them, known as 'foredeeps'.

The origin and history of the great depression which the oceans occupy are still matters for discussion among geologists. Briefly, there are two chief schools of opinion. One of them holds that the continents have moved into their present positions by the drifting apart of portions of a once single whole. The most famous of these drift theories, as they are called, is that put forward by the German geologist Wegener in 1914. According to this theory, there was until Carboniferous times a single continent, Pangaea, made of comparatively light material resting on a denser substratum. In the Carboniferous period, owing to tidal and other forces, this single land mass broke up into separate blocks which, like beeswax moving on pitch—if that can be imagined—slowly drifted into their present position. But there are many objections to Wegener's drift theory and it has now been abandoned. The chief objection is that there is no known force which could cause the splitting apart and drifting of the land masses which the theory involves. There are, however, other theories which introduce the principle of drift into the history of the earth.

There are certain features of the structure of the basin of the Atlantic Ocean which seem to fit in with the idea of a split or rupture at some time between the Old and New Worlds. A glance at a map shows that the outlines of the eastern and western sides of the Atlantic Ocean

seem to be complementary to one another. Further, there is the remarkable median ridge (Plate I) which follows the S-shaped centre line of the ocean basin from Iceland to Bouvet Island nearly within the Antarctic Circle. And there are other geological and biological similarities between the eastern and western sides of the ocean which suggest that they were originally joined.

The other school of opinion, however, holds that all the questions, both geological and biological, which drift has been called in to answer, can equally be answered along orthodox lines. The land masses are considered to have undergone great changes by the foundering of whole continents beneath deep oceans. The Atlantic and Pacific Oceans are believed to have engulfed during the history of the earth stretches of continental land which formerly united their opposite shores.

There is general agreement between those who hold to these more orthodox ideas and those who favour the more recent drift theories that certain broad topographical features of the oceans and continents existed in past ages. There were, for instance, two great continents which foundered into what is now the Atlantic Ocean in Tertiary times. The northern one joined what is now North America to what is now Europe and Asia. This would account for the similarity, and possible continuity, of the eastern and western sides of the North Atlantic. It may be that the Azores, and the submarine plateau on which they stand, are the remains of this lost continent, as Madeira, the Cape Verdes and, perhaps, the Canaries, may be also. Here the lost continent of Atlantis, the legend of which has so long persisted in the historical memory of mankind, was supposed to have

sunk into the waves in the year 10,000 B.C. Geology provides some evidence for it but indicates that it foundered long before mankind appeared on earth.

The other great continent which stretched across what is now the Atlantic Ocean was Gondwanaland, which united the Africa, Australia and South America of to-day. It accounts for many geological and biological similarities between the two sides of the South Atlantic. The many signs of glaciation, belonging to the Carboniferous period, which geologists have found in Brazil, South Africa, India and Antarctica, indicate that this great land mass was covered by an ice cap like that which now covers the Antarctic, and it is believed that in the coal age, the Carboniferous, the South Pole was not far from what is now the pleasant city of Durban in Natal. Gondwanaland too foundered in Tertiary times, leaving as remnants the South Atlantic Islands, including St. Paul's Rocks, South Georgia and the Falkland Islands.

Between these two northern and southern continents was a long median sea, the Tethys, which covered the area now occupied by the central Atlantic, the Alps and the Himalayas. The central Atlantic portion grew by the extension of bays northward and southward in the region of the modern ocean basin, but the floor of the eastern portion of the Tethys became lifted up above sea level, forming vast mountain ranges, the Alps and the Himalayas.

The great difference between the drift and the orthodox theories concerns the Pacific. Most drift theories hold that the Pacific has remained as a permanent primordial depression of the earth's crust. The idea, in fact, was put forward that it is the scar left behind when

the moon was torn out of the earth's substance, but the objection to that is that the moon is too large for its own scar and would not fit into it. Orthodox theories maintain that there was a great Pacific continent, or perhaps two—a northern and a southern land mass separated by a narrow sea. These are supposed to have sunk slowly down beneath the waves in early Tertiary times and that on the western side of the ocean the process is not quite complete.

If we look at the structure of the Pacific Ocean (Plate I) as we know it to-day we can see the ground for this view. On the eastern margin of the ocean an enormous mountain chain, which has resulted from a folding and crumpling of the earth's crust, runs for 11,000 miles parallel to the coast and falls to a narrow continental shelf and slope beyond which is fairly deep water with a depth of mostly over 2,000 fathoms, and off the coast of Peru 3,000 fathoms. On the Asiatic side a wide continental shelf supports a repetition of similar features which generally increase in complexity southwards. Each consists of what is really a submerged arc-shaped mountain chain breaking surface as a festoon of islands. The convexity of each of these arcs is towards the ocean and is usually bordered by a deep trench or foredeep, while between the arc and the mainland is a shallow basin sea. The northernmost of these arcs is formed by the Aleutian Islands enclosing the Behring Sea and bordered by the deep Aleutian Trench. Next come the Kurile Islands enclosing the Sea of Okhotsk and bordered by the Tuscarora Deep—4,875 fathoms or five and a quarter miles. Next is the Japanese Archipelago, enclosing the Sea of Japan and bordered by the Japan Trench, and the Liu-Chiu Islands, south of Japan, enclosing the

Yellow Sea. Farther south the system increases greatly in complexity and there are several arcs which make up the great Philippine-East Indies complex of islands. Well outside these arcs that run close to the coast are yet others of which the most important is that formed by the Ladrone, Mariana and Caroline Islands enclosing the Philippine Basin. New Zealand and New Caledonia form another enclosing the Tasman Sea. So we see that the western side of the Pacific consists of basin seas enclosed by more or less submerged mountain chains. The floor of the Pacific has no median ridge like the Atlantic but large parts of its southern and central areas are raised up to depths of less than 2,000 fathoms. On this raised portion stand innumerable volcanic islands arranged in arc-shaped archipelagoes. Most of them are capped with coral formations or appear only as fringing reefs or atolls of marvellous beauty. The central Pacific also shows the same shallow basins as the western side, but they are completely submerged. It is supposed that the two great masses of land that once occupied this area were studded with huge lakes and shallow, almost enclosed seas. They began to subside in the late Mesozoic or early Tertiary period, sinking on the eastern side first, where the deepest water now is. The ocean floor sank slowly from east to west and the process is not yet complete on the western side, where the basin seas and festoons of islands still remain along the coast of Asia.

All speculations about the history of the earth begin with a spinning gaseous globe which was once our world in its infancy. It has been slowly cooling and contracting ever since its formation from the parent sun, from a gaseous to a molten and at last to a solid state. The

cooled exterior is made of a solid crust consisting of several layers of different density. There was an inequality in the surface of the crust so that the raised nuclei of the continents, made of lighter materials with a denser substratum beneath them, contrasted with the depressed part of the crust in which the waters of the ocean collected.

Whatever the mode of origin of these depressed areas which the oceans occupy, it is certain that they are of immense age. Nowhere on the surface of the globe can we recognize any rocks which resemble in composition the organic oozes which now cover the ocean floor. No part of the floor of the ocean, we must presume, has been raised above the surface since the organic oozes first began to accumulate upon it—a very long time, even as geologists reckon it, for it covers almost the whole period during which life has been evolving upon earth.

The water which collected in the depressed parts of the earth's crust came both from the atmosphere, which surrounded the spinning globe, and from the primeval rocks themselves. The envelope of gas enclosing the hot primitive earth contained a high proportion of water vapour, carbon dioxide and carbon monoxide. Unlike the atmosphere which it later became, and which we now breathe, it contained no oxygen. The water vapour formed a perpetual dense blanket of cloud ever writhing and convoluting into giant thunder-heads from which torrential rain fell continually, only to evaporate back again almost at once on contact with the hot rocks. As cooling went on, however, this rain settled in the depressions of the earth's crust and formed the beginning of the oceans, which were probably warm at first, shrouded in

thick mist and cloud. But there was an additional source of water in the rocks themselves because the water vapour of the primitive atmosphere would have been taken up into the fluid rocks in solution in much the same way as the atmosphere of to-day is taken up into solution in the waters of the ocean. As the rocks cooled and solidified, this water, bound within them, would have been released. Still another source of water would have been that which was held chemically bound in the rocks, for rocks to-day hold water in chemical combination which they are continually releasing. Throughout geological time, therefore, the waters of the ocean must have been steadily increasing in volume. One may wonder that the vast bodies of water that wash our shores and bear our ships can have originated in this manner, but it has in fact been calculated that there is now too little water on the earth for this theory of its origin to be entirely satisfactory. And we must remember, once again, that if the world is reduced to the size of a large orange the ocean becomes a mere wetness on its skin.

Water is an almost universal solvent. Nearly all substances dissolve in it to a certain, though possibly minute, extent. Even the glass is dissolved slightly in a tumbler of water. From its very beginnings the crust of the earth has been subjected to the slow but persistent and inexorable dissolving action of water. Ever since water first collected in the ocean basins the sea has been washing the coasts of the continents and the rain, falling on the land, has been draining into the lakes and rivers. Sea water, therefore, contains in very dilute solution all the elements which compose the minerals of the earth's crust. But, as everyone knows, there is a great difference

in chemical composition between sea water and fresh water, between the water of the oceans and that which drains into it from the land. For instance, fresh water contains far less combined sodium but far more calcium than sea water, far less chlorine but far more sulphate and carbonate. One would imagine, therefore, that sea water must have been changing steadily in composition throughout the earth's history. Yet it is a fact that the amount of dissolved salts which the rivers contribute to the sea every year is only a very small fraction—estimated at about one two-millionth part—of the total in the ocean. And even this is not all gain to the ocean for some of the salts which the rivers carry down are thrown out of solution by precipitation or withdrawn by animals and plants to form skeletons of lime or silica. A certain proportion too is swept off the sea and on to the land by wind-blown spray or picked up by the water vapour of the atmosphere and deposited again upon the land. These are washed into the rivers and so returned to the sea comparatively quickly and are for this reason known as cyclic salts. They reduce the gross contribution which the rivers make to the ocean. Very few of the rivers have, in fact, any effect on the chemical composition of the sea beyond a short distance from their mouths. The Baltic, since it is an enclosed sea, is slightly affected chemically and diluted by the rivers which drain into it, but the Mississippi has very little influence beyond a few hundred miles from its mouth. So we must assume that if the rivers have affected the sea chemically during the earth's history they have been doing so only very slightly and the change has been a very slow one. Sea water, then, is probably not very different chemically to-day from the water which first collected on the young

barren earth. A large part of the salts in that water were derived originally from the rocks of the hot crust at a time when conditions of temperature and sometimes of pressure were more favourable for solution than they are now. They have remained ever since in approximately the same proportions and we must suppose that some chemical mechanism exists, unknown to us at present, which changes the proportions of the various salts to one another when fresh water flows into the sea.

Sea water is a very dilute solution of many mineral substances derived from the earth's crust. It contains also a certain amount of organic salts which come from the decay and excretion of animal and plant bodies. It has been calculated that there are enough salts in the sea to cover the entire globe, when dried, with a layer 150 feet thick or the present land area with a layer nearly 500 feet thick. In this solution common salt (sodium chloride) is by far the most important constituent. An artificial sea water can be made by dissolving in a litre of water a mixture of salts which consists of 68 per cent. common salt and various other salts in very much smaller proportions, but this solution is not the same as true sea water for various reasons. In the first place it lacks certain very important ingredients found in real sea water in small but significent amounts. These are the so-called nutrient salts which are used by plants primarily and animals secondarily in their metabolism and growth. They are mainly phosphates, nitrates and nitrites. In the second place the salts in true sea water are highly ionized—dissociated into electrically charged units or 'ions', so that it is only really correct, when speaking of the chemical composition of sea water, to

refer to the individual ions into which the various salts are dissociated. They may be listed as follows:

	per cent.		*per cent.*
Sodium (Na),	30·4	Chlorine (Cl),	55·2
Magnesium (Mg),	3·7	Sulphate (SO_4),	7·7
Calcium (Ca),	1·2	Bromine (Br),	0·19
Potassium (K),	1·1	Carbonate (CO_3), Bicarbonate (HCO_3),	0·35
Strontium (Sr),	0·04	Boric acid (HBO_3),	0·07

One of the most important discoveries made by the *Challenger* expedition was the surprising fact that although the concentration of the solution, sea water, may vary from place to place over the surface of the globe, yet the proportions in which the different units or ions of the elements exist to one another vary very little whether the sample analysed be taken from the Red Sea, where the salt content is nearly 40 parts per thousand, or from the Baltic, where it is only 7·2 parts per thousand. This is a most useful characteristic of sea water for it means that if we know the amount of one constituent in the solution we can calculate the others and thus the total salt content of any sample of sea water. The total salt content is called the salinity and refers to the total dissolved solids present in solution—including among others the most important ingredient, common salt.

The chlorine present in sea water, together with the bromine and a minute trace of iodine, is very easily thrown out of solution by the addition of silver nitrate. A white precipitate of silver chloride (with bromide and iodide) is formed and this affords a very quick and accurate method of determining the amount of chlorine

in the water. Since the proportions of the other salts are known, it is by this method that the salinities of samples of sea water are determined in practice at sea. This is an extremely important part of routine oceanographical work because salinity is directly related to density and to temperature. Small differences in density, and thus in salinity and temperature, give the clue to the movements of currents and of masses of water in the oceans at various depths beneath the surface.

The uniformity in the proportions of the salts in sea water is brought about by the thorough mixing which takes place all over the globe. For the waters of the ocean are never still. Currents move great bodies of water from one place to another. When water is carried away at the surface by any agency, more wells up from below to take its place. There is also a constant stirring action by the waves and the wind and by cooling at the surface and evaporation which cause vertical convection currents. Yet variations in the concentration of the solution—the salinity—do occur from one part of the ocean to another. In some areas the solution may become more concentrated by evaporation and in others more dilute by the addition of river water, or rain or snow, or the melting of bodies of ice. And these differences are traceable in the deeper layers where, for various reasons, masses of water move away from one part of the ocean into another or sink beneath other masses that lie above them. For any or all of these reasons certain seas are more salty than others. The North Atlantic has an average salinity of 35 parts per thousand ($^0/_{00}$) but the Red Sea, where evaporation is intense, is more concentrated and has a salinity of 40–41 per thousand. The water of the Baltic, on the other hand, is very dilute

owing to the melting of ice and the inflow of many large rivers so that its water is almost brackish with a salinity of only about 7 per thousand. In the Atlantic and Pacific Oceans during the northern summer the surface water is more salty in regions where evaporation is greatest and less so in regions where dilution by snow-fall or rainfall is greatest. The areas of highest salinity correspond roughly with the areas of high atmospheric pressure—the permanent sub-tropical anti-cyclones. Here are clear skies and light winds throughout the year so that active evaporation is always going on. Towards these parts of the ocean blow the strong and constant NE. and SE. Trade Winds. These too cause evaporation and set up currents which carry the water into the high pressure areas. On the western sides of the oceans this saline water is swept away into high latitudes by the great permanent flows such as the Gulf Stream and the Brazil Current in the Atlantic and the Kurosiwo and East Australian Currents in the Pacific (Plate II). Between the two sub-tropical areas where the salinity is high is a narrow belt in the tropics where it is low. This is the region of the Doldrums, a cloudy zone of frequent showers in which dilution of the surface water takes place. Round the Poles there is a belt of low salinity which is due to the melting of vast fields of ice. In the North Atlantic the Gulf Stream carries warm salty water far to the north around the British Isles nearly to Spitzbergen (Plate II) and off the coasts of Newfoundland and Nova Scotia there is a sharp contrast between this water and that which meets it from the Davis Strait diluted by melting ice and snow.

The currents which flow from one ocean region to another are parts of the general circulation of the

hydrosphere which, because of the rotation of the earth, has an eddy form like that of the other non-rigid envelope, the atmosphere.

A particle which is quite free to move over the surface of the spinning globe is deflected towards the right in the northern hemisphere and towards the left in the southern hemisphere. For this reason water or air moving from the Equator polewards in the northern hemisphere takes a north-easterly direction and in the southern hemisphere a south-easterly direction. Two processes go on together in the tropics—heating of the sea water, which makes it less dense, and evaporation, which makes it more saline and so more dense. But the former effect wins so that the surface water tends to stream away towards the Poles while colder water rises up from below to take its place. In cold temperate and polar seas, again, two processes go on side by side. The water cools and ice forms, leaving the salts behind—for sea ice is almost fresh—and this tends to make the water more dense. But water vapour evaporated in the tropics falls as rain or snow and great icebergs from the land drift out to sea, effects which tend to make the water less dense. But the cooling process wins and so, in the Antarctic and, to a lesser degree, in the Arctic, cold water sinks and creeps towards the equator along the bottom. The NE. and SE. Trades, blowing strong and constantly across leagues of ocean, help the great current eddies north and south of the Equator. They give the surface water, which tends to flow north and south from the tropics, a westward direction. Thus the westward flowing North and South Equatorial Currents (Plate II) are formed with an easterly counter current between them. In the Atlantic the northern one piles up in the Gulf of Mexico and pours

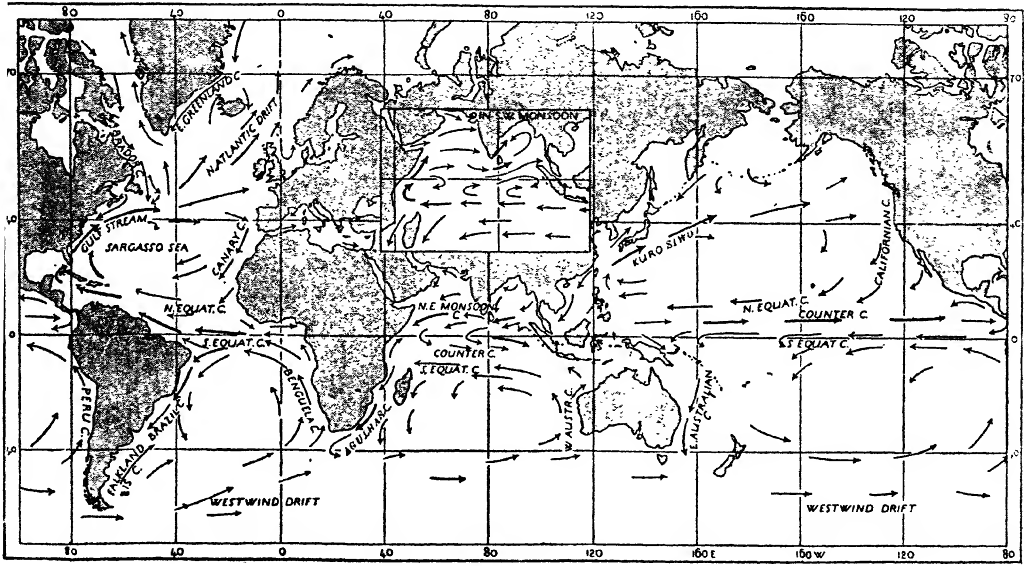

Plate II. Surface Currents.

out as that great river in the ocean, the Gulf Stream, flowing at the rate of five knots through the Florida Strait and carrying the blessing of warm water to the northern coasts of Europe (Plate III). The southern Equatorial meets the coast of Brazil and turns south. In the Pacific the Kurosiwo, flowing from Japan towards California, is the counterpart of the Gulf Stream, though on a much smaller scale, while the East Australian Current is the counterpart of the Brazilian. In the Indian Ocean the South Equatorial Current turns south along the coast of Africa as the warm Agulhas Stream, but over the north Indian Ocean the currents change from NE. to SW. with the monsoons. Over the Southern Ocean the west winds sweep unhindered round the globe and push the surface water before them as the slow but massive West Wind Drift—a great movement of surface water east and north over almost the whole extent of the southern temperate latitudes. Where the southern continents project into it the West Wind Drift sends branches north along their western coasts. Close to the Antarctic continent easterly winds prevail and push before them a westward current, the East Wind Drift, which flows along the coast into those great bights, the Ross and Weddell Seas, where it turns clockwise out into the open ocean.

A ship moving southwards along any meridian does not pass by slow degrees from the sunshine to the bleak grey skies of the Southern Ocean. In about 50° S. latitude there is a sudden change. The sun vanishes and the sky takes on a sullen and cheerless grey. If you take the temperature of the sea with a bucket and thermometer just before and just after this change you find that it marks a sudden drop of between 2° and 5° C. There is

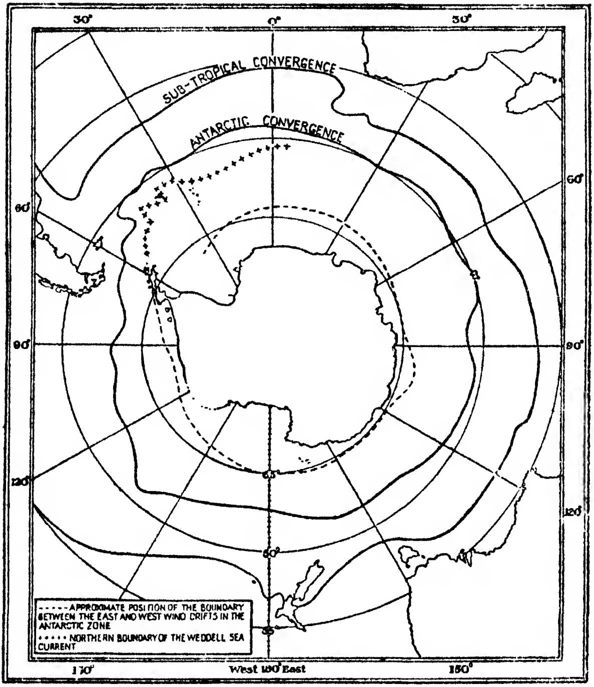

FIG. 2. The Southern Ocean showing convergences.

in fact a boundary line around the Southern Ocean in about this latitude which is of the greatest importance to all marine life. It is as effective in dividing the populations on the two sides of it as a mountain range on land. Even the birds on either side of the line are different. This boundary is called the 'antarctic convergence' (Fig. 2) and it marks the line where dilute but cold, and

therefore dense, water of the West Wind Drift meets with the more saline but warm and therefore lighter water of the sub-antarctic zone. Farther north again in about 40° S. latitude another similar but much less well developed boundary marks the line where warm sub-antarctic water meets the still warmer sub-tropical.

In the southern hemisphere the circulation of the ocean has a grand and planetary simplicity. There are few obstructing land masses except where South America projects to within 600 miles of the Antarctic Continent. The West Wind Drift, sweeping round the world under the influence of 'the brave west winds', forms a layer of cold surface water 300–800 feet in depth moving north and east. At the convergence (Fig. 2) this layer sinks and flows north beneath the warmer and lighter surface water of the sub-antarctic. Below the surface layer of the West Wind Drift is another moving south and east. This is water which has sunk down from the North Atlantic spreading out slowly towards the south. Along the bottom of the Southern Ocean very cold and dense water, cooled in the far south, creeps slowly along the bottom north and east, reaching at last the northern hemisphere where it can still be traced. The simple plan of circulation in the south, then, is that water flows north from the Poles at the surface and at the bottom, but there is an intermediate layer between these two of water flowing south from the Equator, sinking towards the Pole.

In the north the circulation is very much more complicated. There are land masses which obstruct and deflect the flow of currents and ridges that cut off the water at the bottom of neighbouring seas from the main ocean. There are seas like the Mediterranean and Red

Sea which pour into the ocean dense saline water which spreads out in the deeper layers. So the simplicity we find in the south is lacking, but there are nevertheless certain well defined boundaries between different masses of water. In the North Atlantic there is the very pronounced cold wall separating the water of the Gulf Stream from that of the Labrador Current. There is another boundary separating the NE. Trade Drift from the Gulf Stream west of the Sargasso Sea. In the Pacific there is a much less well defined cold wall between the Kurosiwo and the cold waters of the Behring Sea.

These circulating movements of the hydrosphere are due to the rotation of the earth, to the influence of prevailing winds—themselves an effect of the earth's rotation—and to the great land masses that divide the oceans. But there are other movements of the hydrosphere which are due to the gravitational pull of the heavenly bodies that surround the earth in space. These are the tides, the causes of which are well enough known in a general way. Briefly, all the heavenly bodies exert some attractive force on the earth, but the influence of all except the sun and the moon is insignificant because of their distance away. The moon, since it is so much nearer to the earth, exerts about twice the pull of the sun. The moon attracts the side of the earth nearest to her more strongly than the centre. But the earth is a rigid body and, though there are movements of the earth's crust in response to this pull, yet they are so small that they can only be detected by special instruments. The envelope of the hydrosphere, however, is not rigid and becomes heaped up in the direction of the moon's pull. On the side of the earth away from the moon the surface of the globe is attracted less than the centre and

the hydrosphere less than either so that the water becomes heaped up here also. When the earth, sun and moon are in line or syzygy, which happens once a fortnight, their combined pull produces the largest movement of the water, the spring tides. When the three bodies are at right angles (quadrature) we get the smallest movement, the neap tides. This too happens once a fortnight. The earth rotates on its axis once in twenty-four hours and each meridian in turn comes opposite the moon, so that in each rotation of twenty-four hours there are two high and two low tides with roughly six hours between a high tide and the next low. According to the old tidal theory, held for many years, there sweeps round the Southern Ocean as the earth rotates a pair of tidal waves. One of them is opposite but following slightly behind the moon and the other diametrically opposed to it on the surface of the globe. The three major oceans could be looked upon as bays leading off the Southern Ocean into which offshoots of these tidal waves pass northwards. But this theory is no longer held. In different parts of each ocean, it is now believed, the tides oscillate about tideless nodal areas rather as the water in a dish, tilted and swirled round a little, sinks on one side and rises on the other, rocking about a central portion where there is neither rise nor fall.

Finally, we must mention the waves caused by the action of the wind on the surface of the sea—the most familiar and at times the most spectacular of all the movements of the hydrosphere. A wave is an oscillation of the water particles at the surface but the water itself is not involved in the forward movement which we perceive when we watch the wave. A cork floating on a pond in which there is no current bobs up and down

upon the waves but, unless it is pushed along by the wind itself, it changes its position only very slowly. Each water particle describes a circle as the wave passes it, advancing slightly on the crest and then returning in the trough almost though not quite to its original position, so that there is a very slight forward motion. Just how this oscillation starts from a smooth surface with a light wind travelling parallel to it is still not certainly known but, once formed, the wave grows by pressure of the wind against its windward slope. It grows swiftly at first and then more slowly. When the height of the wave has reached about one-seventh of its length from trough to trough the crest becomes a ridge and curls over so that a short wave soon breaks, but the longer a wave is the higher it can grow before breaking. When a wave runs into shallow water its base becomes retarded so that the front slope steepens until finally the upper part is a sharp ridge which curls over and breaks. When the wind drops or when the waves run out of the storm area they become rounder and more regular. They change, in fact, from waves to swell. They may travel as swell enormous distances and storms off the coast of Newfoundland have been followed by swells off the coast of France heavy enough to cause damage to harbour works. The famous rollers of Ascension and St. Helena have caused great damage even though they have travelled three or four thousand miles. Swells in the open ocean a thousand feet in length and thirty or forty feet in height are common while the longest swell actually recorded is 3,700 feet from crest to crest. In the North Atlantic during the recent war naval ships have estimated the height of waves at over fifty feet. Ingenious instruments for measuring the length and height of waves have been

developed during the war when the prediction and forecasting of swells on beaches became important for landing operations. One of these instruments is a sensitive pressure recorder on the sea bottom which registers the slight changes in the hydrostatic pressure as the waves pass over it. Another is an echo-sounding recorder on the bottom which records the echo profiles of the surface.

CHAPTER II

LIFE IN THE SEA

Protoplasm—Difference between animals and plants—The beginnings of life—The sea as a medium for life—The body fluids—Nutrient salts in the sea—Transparency—Sea water as a buffer solution—Oxygen content—Uniformity of temperature and density.

THE SEA is a realm of life even more populous than the dry land. Not only the seashore and the banks which are the home of many sorts of fish but the open ocean also, many hundreds of miles from land, supports a plant and animal population of the greatest diversity and complexity.

The basis of all living bodies, including our own, is protoplasm—the physical basis of life as Huxley named it. Very little is known about the physical and chemical properties of protoplasm since it can only be studied when it is dead and it is then no longer the same substance as it was when alive, but one of its unique properties is its power of obtaining certain elements—carbon, hydrogen, nitrogen, oxygen, phosphorus, sulphur and iron—from the world around itself and of building them up into large protein molecules. It also builds up carbon, hydrogen and nitrogen into carbohydrates. It is this property which we imply, among others, when we speak of anything being alive. The difference between plants and animals lies in the manner in which this building up process takes place. Plants draw up the necessary salts in solution in water by means of their roots for the

formation of the proteins within their cells. But they have developed the power of forming carbohydrates from carbon dioxide and water, using the carbon dioxide of the air or water which surrounds them. This they fix by means of the green substance, chlorophyll, in their leaves. It acts as a catalyst, absorbing energy from the sunlight to activate the water and CO_2. This process, which is common to all green plants both in the sea and on the land, is called photosynthesis. It follows, then, that plants continually absorb and use up CO_2 and, as a product of the chemical reactions which take place in photosynthesis, they give up oxygen. But, like all other living things, they carry on the parallel process of respiration, using up oxygen and giving out CO_2 and water.

Animals, unlike plants, can only obtain their proteins and carbohydrates from the bodies of other animals or plants. They can neither take in food in solution nor synthesize it with the aid of sunlight. Accordingly they must take in solid organic food and then, inside their own bodies, change it chemically into the necessary proteins and carbohydrates.

There is no direct evidence as to how or where life first began on earth. The very earliest fossils, those of the oldest Cambrian deposits laid down perhaps 500 million years ago, are the remains of animals already high enough in the evolutionary scale to have had external skeletons and shells. The soft parts decay away and leave no trace so that only such faint signs as worm casts or traces of burrows remain to tell us what soft bodied animals peopled the seas at that time. We can only guess what these were like by analogy and deduction from the living things around us to-day.

The sea is so excellently suited to the development and maintenance of life that it is natural to look upon the shallow coastal seas as its birthplace and cradle. The sea has probably always been much the same both chemically and physically as it is to-day and we must believe that somewhere in it, somehow, under the correct conditions of temperature and sunlight, and in the presence of the necessary elements, protein molecules probably began to build themselves up and went on doing so until they developed the properties of assimilation and growth that we now recognize as characteristic of life. Naked and undifferentiated units of protoplasm came to exist and the seas, probably near the shores where the water was rich in dissolved salts, became peopled with simple single-celled creatures. Here, in the bright sunlight of these shallow waters, some of the earliest inhabitants of our globe developed the green pigment which enabled them to utilize sunlight to build up carbohydrates. Others, on the other hand, added to their own substance by the simple but effective process of devouring that of their fellows. In this way the first distinction between animals and plants arose.

Now the sea is an ideal medium in which the subtle and delicate chemical processes could go on, leading up to the beginnings of life. It is a medium, too, in which the lowliest, most fragile and most vulnerable forms of life can readily exist. It is populated to-day by great numbers of simple primitive creatures with fragile tissues, unsupported by skeletons or unprotected by outer coverings, highly sensitive to chemical and physical changes in their environment. They could only have developed in a dense homogeneous medium such as the sea presents. Protoplasm consists of about 80 per

cent. water. All animal and plant bodies, therefore, contain about this proportion of water and must maintain it. If it falls too low the cells dry up and we ourselves know what distress results from even a slight lowering of our water content which we experience as thirst. Land living animals and plants have developed many devices for carrying water to all parts of their bodies and for preventing their tissues from drying up, such as thick protective skins, fleshy tissues and elaborate vascular systems which carry water to all parts of the body. On the other hand too much water is equally undesirable for it results in engorgement of the cells and there are almost as many devices among higher animals and plants for getting rid of water as there are for retaining and distributing it—for example, the kidneys or elaborate evaporating surfaces. But in the sea there is no danger of the tissues either drying up or becoming engorged. In the lower forms the benign medium in which the creature lives bathes it and supports it in every part and comes into close or direct contact with the cells. In the higher forms the cells are bathed by the blood or the body fluid. The cell wall is a semi-permeable membrane through which water, but not the salts dissolved in it, diffuses in or out of the cells and so maintains an osmotic balance between the protoplasm within and the sea water, blood or body fluid which bathes it. It is perhaps one of the most convincing arguments for the dawn of life in the sea that the salts in the blood and body fluids of all animals are roughly the same as those in sea water and are present in approximately the same proportions. This is an extremely important fact of life in the sea for it means that the external medium and the internal one that bathes the cells in higher forms are at

the same osmotic pressure. No great amount of energy need, therefore, be spent by marine animals (except fishes) in keeping the body fluids at the proper concentration.

The sea is a nutrient solution. It contains dissolved in it, usually though by no means always in sufficient quantities, the necessary mineral salts for the building up of proteins within the bodies of plants and of low undifferentiated forms of life. These salts are various nitrates, nitrites and ammonium salts, which provide the necessary nitrogen, and phosphates, which provide the phosphorus, but they owe their existence in the sea to that very plant and animal life which makes use of them and therefore they are in a state of constant circulation. They originate from the excretion and from the death and decay of animal and plant bodies. In the spring, which is the time for a great outburst of plant and animal life in the sea just as it is on land, these nutrient salts are to a large extent used up. Later in the summer when the plants and animals begin to die the salts are returned to the sea again. In view of this continual circulation of salts, consumed by living things and then later returned to the sea by their excretion and death, one may wonder how the earliest forms of life found sufficient nutrient substances to start the process in the first place. A small proportion of the nutrient salts in the sea is carried down by the rivers and comes from solution out of the rocks. In the sea to-day this is all used up by plant life in the river mouths and has very little effect on the salts in the sea beyond a short distance from the shore. But we may suppose that it was these salts that the earliest living things were able to use.

In clear tropical waters the sea is transparent to a

depth of about 300 feet. It was this transparency which enabled the earliest plants to make use of the sunlight at the surface and to build up their carbohydrates by photosynthesis. This is of fundamental importance in the life of the sea, for upon the plants, which are in a sense the primary producers, the whole structure of marine life depends. The vast multitudes of minute animals feed on plant food and thus make use only second hand of the salts in solution in the water. When the divergence of plants from animals took place there were abundant supplies of carbon dioxide readily available for the plants to use in photosynthesis. The carbon dioxide in the sea is mostly held chemically bound as carbonates, bicarbonates and carbonic acid. Within the transparent surface layers the photosynthesis of plants withdraws CO_2 from the water. This leads to the breakdown of the carbonates and bicarbonates and, as a result, to the setting free of CO_2 into the sea water to replace what the plants use up. The effect of this, if carried to excess, would be to make the water more alkaline, as indeed it does in some rock pools or close in shore where the growth of seaweed is heavy. Now most animals and plants, especially the more delicate ones, are very sensitive to such changes and are soon killed if the water becomes too acid or too alkaline. In fresh water aquaria minute adjustments of the acidity of the water are necessary to keep the animals healthy. Sea water, however, most fortunately for all the creatures that live in it, is extremely resistant to changes of acidity —or of alkalinity, which is another way of saying the same thing. It is what is known as a buffer solution. Large quantities of CO_2 can be withdrawn from it without making it excessively alkaline and added to it

without making it excessively acid. If many animals are crowded together in a small volume of sea water their combined respiration, giving off large quantities of CO_2 into the water, can go on for a comparatively long time before the water becomes too acid to support life.

In the surface layers within the range of daylight the minute microscopic plant life uses up CO_2 and at the same time gives off oxygen as a result of photosynthesis. The surface layers of the sea therefore contain almost as much oxygen as the water can hold at any particular temperature. The water is, in fact, almost a saturated solution as far as oxygen is concerned. Part of this is the result of plant activity and part is dissolved from the atmosphere and is in delicate balance with the oxygen in the air. When life first began all the oxygen in sea water must have come from the atmosphere alone and we may notice in this connexion that when air is dissolved in sea water the dissolved mixture of gases contains a higher proportion of oxygen (34 per cent.) to nitrogen than exists in the atmospheric mixture (21 per cent.).

The oxygen in sea water is available for use in respiration by all forms of life and is carried to all depths of the ocean by the stirring agencies which are continually at work—the currents bringing water from one part of the ocean to another, the sinking of masses of water cooled at the surface and the upwelling of cold water from below, and the action of winds and waves in keeping the surface layers in a constant state of motion. Below the upper 300 feet the amount of daylight which penetrates becomes rapidly less and plant life accordingly diminishes so that the amount of oxygen used up by the respiration of animals, and of such plants as live in these

dim levels, begins to overtake that given off in photosynthesis. At a certain depth, which varies greatly from place to place according to local conditions, the oxygen given out and that used up equal one another. This is called the compensation point. Below it down to about 3,000 feet the amount of oxygen in the water steadily decreases, for less and less is given out by plant activity, but it is still used up by the respiration of animals. In addition it is at these levels that the decay of myriads of slowly sinking animal and plant bodies takes place. Decay, like respiration, is an oxidizing or burning-up process, in which oxygen is used up and CO_2 given out. Below about 3,000 feet the soft parts of all the plants and animals, softly settling downwards, have all been decayed or oxidized away and only the hard skeletons continue their journey towards the bottom. The oxygen content of the water below 3,000 feet therefore begins to increase again to nearly the amount that exists at the surface. Except for a layer between 300 and 3,000 feet, then, where special conditions exist, the sea is fully oxygenated down to the bottom and, since it is kept constantly mixed and stirred up, never becomes stagnant—that is, deficient in oxygen. In some Norwegian fjords, however, the water at the bottom is cut off from the outer sea by a sill across the entrance so that it is not constantly renewed and the oxygen content falls. And in the Black Sea, cut off from the Mediterranean by the shallow Bosphorus, the water at the bottom contains almost no oxygen but quite large amounts of poisonous hydrogen sulphide from rotting animal and vegetable matter.

We have seen, then, that the sea is excellently suited chemically for the beginning of those processes by which

life probably first came into being and that, as life became established and as living things multiplied, the surrounding medium must have become more and more chemically suitable and self-renewing with respect to both nutrient salts and available gases. But the sea is as well suited physically as a medium for life as it is chemically. In the first place water has a very high specific heat—in other words, a very great deal of heat must be added to it to raise its temperature. Indeed this is a matter of common experience. Everyone knows that a flame takes very much longer to raise the temperature of a glass of water than it does to raise that of a piece of metal to a point at which it can no longer be held in the hand. Conversely water can give up a great deal of heat without a violent drop in temperature. Animals and plants, especially the delicate naked lower forms, are sensitive to changes of temperature and most of them can only carry on successfully between rather narrow limits. Small increases of temperature speed up the vital processes of reproduction and growth and small decreases slow them down, but, outside the limits peculiar to each species of animal or plant, life ceases. In the sea the changes of temperature which occur from place to place and season to season are small compared with those that take place on land. The height of summer and the depth of winter never change the surface temperature of the open sea anywhere more than 10° C. (50° F.) and usually the seasonal difference is much smaller. The hottest seas in the world are the Red Sea and the Gulf of Oman where temperatures of over 30° C. (86° F.) are common, while the coldest seas are in the Antarctic where temperatures of −1·5° C. (29·3° F.) are usual in the higher latitudes. But this is a small range compared with that

on land where the temperature may vary from 40° below freezing on the Antarctic continent to 150° F. (65·5° C.) in the deserts of central Asia and where a change of forty or fifty degrees Fahrenheit from day to night is a common experience. Furthermore the extremes of temperature at sea are only met with over comparatively small areas. Over the vast stretch of the temperate latitudes (Plate III) the range of temperature at the surface of the sea is from 0° C. to 15° C. (32–59° F.) and if we include the sub-tropical latitudes the range is increased to 25° C. (77° F.). In tropical and sub-tropical waters the temperature falls rapidly below the surface so that even in those tropic regions where the surface layer has a temperature of 25° C. or over, the temperature at 1,000 feet is below 10° C. The sea, therefore, affords an enormous area, two-thirds or 70·8 per cent. of the surface of the globe, over which equable and stable temperatures prevail and in which no shocks due to abrupt or excessive changes of temperature can occur to upset the delicate adjustments of the lower forms of life. Marine animals, however complicated they may become in response to their environment, need never adopt those elaborate measures to protect themselves against changes of external temperature which become necessary for land animals—such as protective coats and sweat glands. Fragile naked eggs can be shed into the sea and their frail embryos and larvae can develop without the need of any such protection. They can be carried over vast distances in the ocean without ever meeting with changes of temperature conditions too drastic for their development. Thus there is an immensity of space in the sea, room for a vast multitude, and indeed the geographic range of most marine animals and plants is very wide.

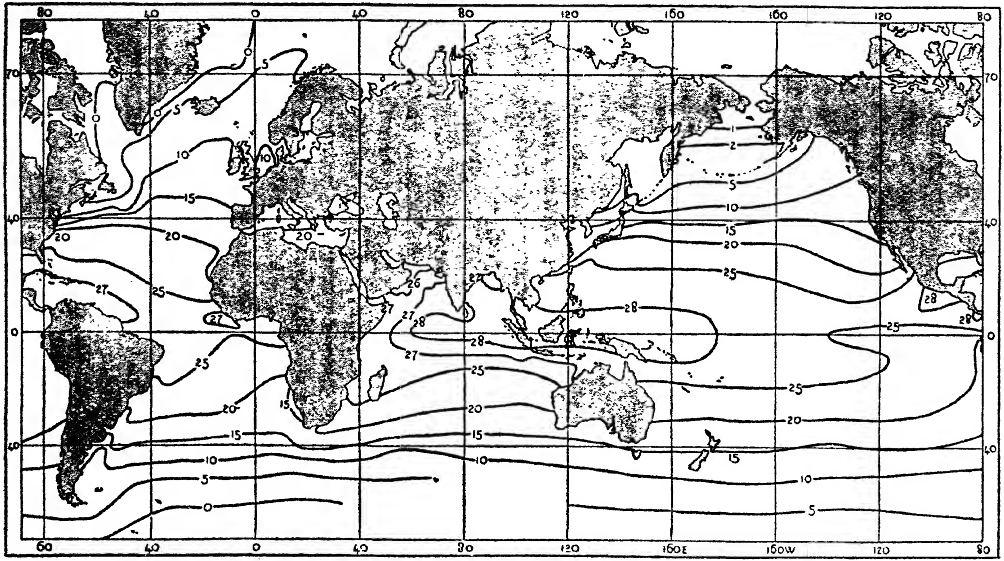

PLATE III. Mean Surface Isotherms (Centigrade).

D

Most eggs and larvae have a specific gravity not very different from that of the sea water in which they develop. The density of the sea, which depends on the salinity (or degree of saltness) is uniform within narrow limits over vast stretches of the ocean. It is only when fresh water mingles with sea water in estuaries or close in shore that alterations in the density of the water seriously interfere with life in it. If the density decreases too greatly, eggs and larvae can no longer remain afloat but sink to the bottom. The difficulty can be overcome to some extent by increasing the surface of the animal or plant in proportion to its volume and for this reason, in the tropics where the water is warm and less dense than in temperate or polar regions, animals and plants with a floating habit tend to develop long and often bizarre filaments and processes to increase their flotation surface in relation to their volume (Fig. 3).

We have seen, then, that the sea was the birthplace of life where the tiny germs of protoplasm took shape and grew in size. They split and split again to give rise to ever more undifferentiated units. From them the entire great tree of life arose and spread its branches throughout the earth. Its crowning branches are under Heaven, so we like to persuade ourselves, for there stands man himself, the goal perhaps to which all the aeons of slow development have been leading. But the roots of the tree are in the ocean and there its first seeds and faint beginnings may still be traced. Forgotten and left behind in the race the lowly and humble forms remain as living witnesses, gazing upwards unenviously, we may believe, at their more lofty cousins and descendants in the upper branches. For, humble though these creatures of the sea may be, they are perfectly adapted to their

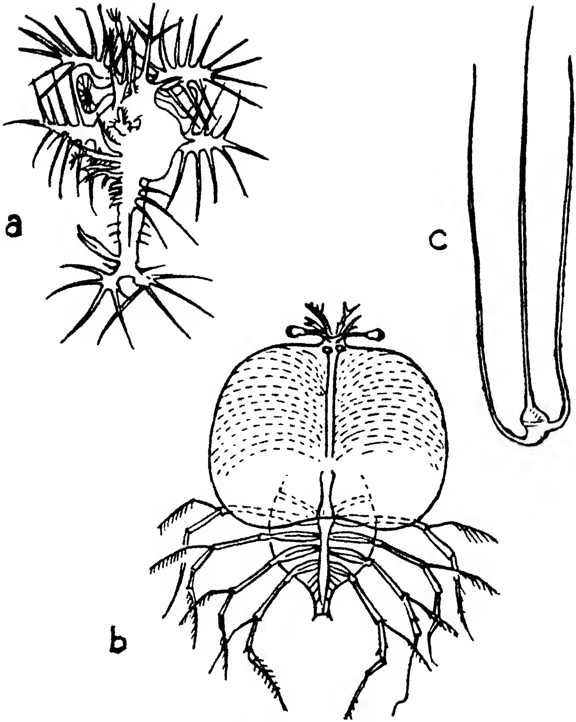

FIG. 3. (*a*) Larva of Sergestes, a deep sea prawn (x 20 approx.); (*b*) Phyllosoma larva of a rock lobster (Scyllarus) (x 1½ approx.); (*c*) the dinoflagellate Ceratium tripos (x 40 approx.).

environment. They progressed no farther for the very reason that they were perfectly successful where they found themselves. They have found the answer. And no race of animals or plants, the human race not excluded, survives for long that cannot find it.

CHAPTER III

THE PLANKTON

Plankton, nekton and benthos—Plant plankton—Diatoms—Dinoflagellates—Other plants—Macro-, micro- and nannoplankton—The permanent plankton—Foraminifera—Radiolaria—Copepoda—Chaetognatha—Euphausiidae—Other zooplankton—The temporary plankton.

THE LIVING creatures of the sea are divided for convenience, according to their habits and manner of life, into three classes. One class, perhaps the largest and most important owing to its fundamental position in the economy of the sea, comprises all those vast swarms of plants and animals which have only limited powers of movement of their own or none at all, but yet are not fixed to any substratum and which therefore drift more or less helplessly at the mercy of tides and currents. This class iscalled the plankton (Gr. πλάνκτον, wandering). The second class comprises all those animals, such as whales and fish, which swim powerfully enough to be to some degree independent of tides and currents. This class is called the nekton (Gr. νηκτόν, swimming). The nekton naturally contains no plants since by definition plant life has lost the power of motion and all marine plants either drift near the surface or remain rooted to the bottom. Thirdly, there is the class of animals which creep upon the bottom or burrow into it or remain fixed to one spot. These are called the benthos (Gr. βένθος, deep). One may, perhaps, if one wishes, include among the benthos the seaweeds which spend their lives rooted

to the rocks, but the term is usually applied to the animal life of the bottom, to things that crawl or creep or burrow or fix themselves by some part of the body.

This is a very loose and flexible classification. It is intended only as a frame in which to enclose our picture of life in the sea which would be shapeless without it. It forms a foundation upon which to build. Each of the three arbitrary divisions contains animals from many classes and each class may contain orders which belong separately to the plankton, the nekton or the benthos.

Upon the plankton, and upon its seasonal and regional variations in abundance, depends the whole economy of the sea. The vast fisheries of the coastal banks and the whale herds of the Antarctic depend on the movements and fluctuations of the plankton which forms the staple food of so many different creatures, from the great whales and the herring down to the tiny fry of the cod and the krill which the whales devour. We must therefore deal with the plankton first and sketch in the rest of the picture against this vast and profuse background.

Travellers towards these islands, a day or so out from our shores, notice that the blue or grey waters of the Atlantic have changed to an opaque green. Those returning homeward behold this with a lift of the heart for it is for them, as is the veiling of the sun in cloud, the first familiar sign of England—the green of her Channel. If the traveller could lower into that water a net or a bag of silk—unlikely though it may be that he could do such a thing—he would bring it up choked with thick green slime. But had he been able to do this off the coast of Portugal, for instance, he would have brought his net

up fairly clean. The green slime which seems to fill the Channel water looks like mud. Indeed, the Greek explorer Pytheas, who sailed as far north as Thule (the Shetlands) during the lifetime of Aristotle, declared that the sea in those cold and foggy regions was muddy and sluggish. Sometimes the slime is a pale emerald green, sometimes grass green and sometimes very dark, almost brown. It is, in fact, the living grass of the sea—for all the temperate seas, especially the shallow waters near the coasts are, to use an expression which has almost become a cliché, the pastures of the ocean. They are exceedingly rich in this floating green plant life—the phytoplankton—which gives the waters of our Channel their heartening and well-remembered hue.

Under the microscope the green substance of the plant plankton takes on a beautiful and fantastic appearance. A small spot of it, separated out in a drop of water, shows a very large number of little rods or spicules or discs or cylinders or other shapes too diverse to describe (Fig. 4). They may be sculptured or pitted or adorned with spines or with hairs. They may be single or, more usually, grouped together in chains or bundles. Their variety and exquisite design, minute but perfect, seems almost infinite. Yet all these microscopic entities belong to a single plant family, the diatoms, and therefore they have certain important features in common. Their intricate skeletons are made of silica (glass) and no matter what their elaborations and ornaments, whether they bear spines or hairs or sculpturings, yet they are plainly made up of distinct individual units or cells, usually arranged in chains or bundles. Each cell consists of a little glass box made of two parts or valves which fit nicely into one another and enclose between them a

unit of living protoplasm. The protoplasm is in communication, through a slit in the box or through pores in the valves, with the sea water outside and thus can carry on all those processes of exchange, of gases and of salts, which are necessary for life. It contains particles of green substance which carry on the activity of photosynthesis, characteristic of plants, with the aid of sunlight. The diatoms reproduce themselves simply enough and do so with enormous rapidity in the spring. The cells divide in half—one daughter half taking the smaller valve of the glass box and the other half taking the larger, the lid, as it were, of the box. Each then becomes the lid of a new cell, a new smaller valve or bottom of the box being formed to fit it. It follows, therefore, that as division is repeated over and over again during the summer the cells get smaller and smaller and this continues until they reach a certain size which appears to be the limit of smallness. If they divide any further, deformities begin to appear and the cells begin to die off. This is evidence of failing vigour in the population and, in order to restore it, a rejuvenating process must take place. Accordingly some of the cells bulge out from between their valves as large swollen masses, each in a flexible distensible membrane, and these separate off and grow new shells. In this simple way they regain at one bound their former size and, apparently, their original vigour and begin dividing again. If living conditions become unfavourable for any reason, if the sea becomes too cold or if the nutrient salts on which the plant lives fail, the diatom cells round themselves off, each enclosed in a thick case, made of silica like the valves, and sink to the bottom. These are the resting spores which can resist months of inclement conditions

and can withstand cold or heat or even drought. When conditions improve they come to life again.

The diatoms are by far the most important and the most abundant members of the plant plankton but there are others, including some which are on the borderline between plant and animal life. These, though of secondary importance in the economy of the sea, often occur in sufficient numbers in warm and temperate waters to change the colour of the sea.

The dinoflagellates (Fig. 4) are important because they form the food of some fishes such as the pilchard and the sardine. Like the diatoms they form the food of the animal plankton and are sometimes present in such numbers as to colour the water. They, too, consist of single cells, microscopic but considerably larger than the diatom cells, but they do not as a rule cling together to form chains except temporarily after reproduction which, again, is the simple process of division. Some live like plants and contain within them corpuscles of green, yellow, brown or even pink pigments that carry on photosynthesis. In this respect these dinoflagellates resemble plants, but there are others which ingest diatoms or each other or even small animals, taking them whole into their protoplasmic bodies. These might, for this reason, be placed in the animal kingdom. Some, on the other hand, are capable of both processes and are truly on the borderline between the plants and the animals. The most characteristic feature of the dinoflagellates, uniting them all, is the whip from which they take their name. A long vibratile thread of protoplasm lies in a meridional groove on the body and trails behind as the creature moves through the water. Another lies in a groove placed more or less equatorially.

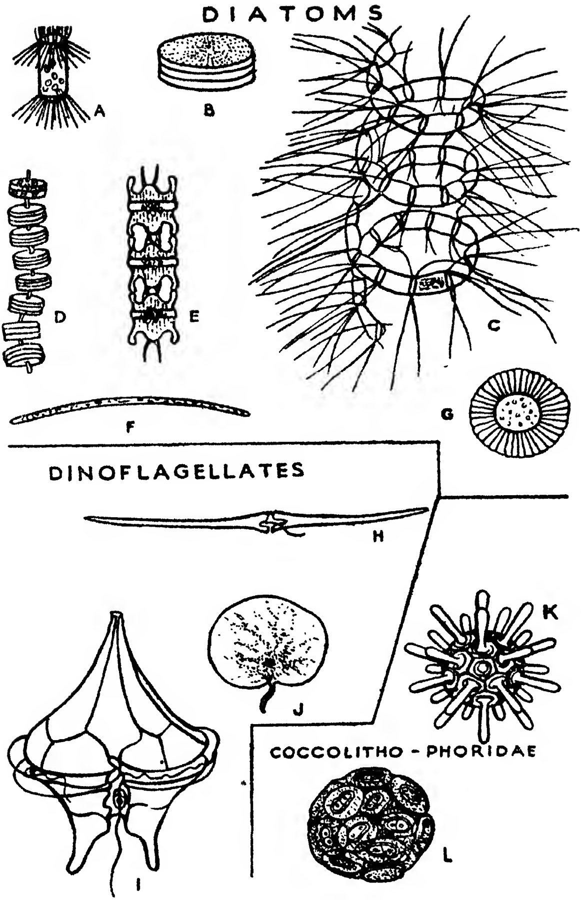

FIG. 4. Diatoms (x 100–500 approx.): (*a*) Corethron, (*b*) Coscinodiscus, (*c*) Chaetoceros, (*d*) Thalassiosira, (*e*) Biddulphia, (*f*) Thalassiothrix, (*g*) Planktoniella. Dinoflagellates: (*h*) Ceratium fusus (x 25 approx.), (*i*) Peridinium (x 300 approx.), (*j*) Noctiluca (x 50 approx.). Coccolithophoridae (x 1200 approx.): (*k*) Rhabdosphaera, (*l*) Coccosphaera.

These by their ceaseless movement lash the little cell along.

One of the most striking dinoflagellates is the large single-celled spherical creature, *Noctiluca* (Fig. 4*j*), which causes the phosphorescence of warm seas. It is a large naked globe of protoplasm, pale pink in colour, with a single stout tail with which it whips itself along. It has definitely animal affinities since it feeds by ingesting quite large particles which it engulfs through a funnel-like aperture in its protoplasmic body, and it has the property of giving out a pale light. Sometimes in warm waters it may be seen in such numbers on the surface, blown by the wind and waves into patches and streaks, that the sea has rather the appearance of tomato soup and at night glows with a milky luminescence. *Pyrocystis* is a larger and more brilliant form. In another group of dinoflagellates, the peridinians (Fig. 4*i*), the protoplasmic body is encased in an armour of plates made of a substance resembling cellulose. The formation of cellulose is a plant characteristic—it forms the cell wall and therefore the body framework of all green plants. But the peridinians feed by ingesting whole particles and so must be classed as borderline forms. In some (*Ceratium*) the skeleton is drawn out into relatively gigantic horns and spines (Fig. 3). The peridinians are found mostly in warmer seas and it is they which are sometimes devoured in great quantities by the pilchard and the sardine.

In temperate coastal waters fishermen's nets sometimes become clogged with the gelatinous masses of a plant—*Phaeocystis*. In the large bulging shapeless masses of jelly, which float on the surface of the water, are embedded innumerable microscopic greenish brown cells,

sometimes in such numbers as to give a brown colour to the water. They reproduce by forming spores which escape out of the jelly by means of their two short filaments.

The smallest members of the plant plankton are the Coccolithophoridae (Fig. 4). They are so small that they pass through the meshes of the finest silk nets, but they too are occasionally encountered in large enough numbers to give the sea a milky appearance. The minute cells, each with a pair of vibratile whips, are protected by skeletons of great beauty and variety made of rounded plates with processes projecting from them which may take the form of rods or spines or may even have a trumpet shape. The plates with their strange processes were known, as coccoliths, long before the living cells to which they belong were discovered by Sir John Murray. The coccoliths had been taken in dredgings from very great depths made by H.M.S. *Challenger* and Murray discovered the living cells by hanging fine threads of silk in glasses of sea water so that the minute cells became entangled in them. Although they are so small they are sometimes important as the food of certain animals of the plankton which feed by straining microscopic particles out of the water by means of a delicate filtering apparatus as do the salps which we shall mention shortly.

Two other microscopic plants perhaps deserve notice. One is the green single cell known as *Halosphaera*, which is sometimes found in very great numbers in the tropics and in the colder seas. In the Antarctic it is occasionally, though not often, more abundant locally than the diatoms. The other plant, *Trichodesmium*, consists of reddish-brown thread-like cells which cling together in

bundles. It is seen sometimes floating in large red masses in warm seas and it is from the occasional outbursts of this plant that the Red Sea gets its name.

All these plants, but above all the diatoms, form the food of a great multitude of animals which make up the animal or zooplankton. Although the plant plankton, by swift and simple proliferation, attains a vast profusion of individual cells, the numbers of orders and families into which the floating plants can be grouped is small compared with the diversity of the animal plankton. So great is the range of structure and so numerous the various orders and families to which the animals of the plankton belong that in this small book no more can be attempted than a brief mention of some of the more important and dominant of them.

Most of the animals of the plankton are very small—many are microscopic. Nevertheless the range of size is enormous, for, while some are so minute that they pass through the meshes of the finest silk nets yet, at the other end of the scale are great jelly-fish, such as *Periphylla*, taken in deep water in the Atlantic, which may be two or three feet in diameter, or the 'Portuguese men o' war' that sometimes drift inshore on Mediterranean coasts and make bathing dangerous. These may have floating bladders eighteen inches in length with stinging tentacles trailing behind them for a distance of twenty or thirty feet. So we classify the zooplankton roughly according to size into three groups—the macroplankton, the microplankton and the nannoplankton. The macroplankton includes all those animals which are readily seen with the naked eye and which cannot pass through the meshes of a coarse canvas net. The microplankton consists of animals which cannot be seen easily without

a lens or microscope and which are held by the meshes of the standard type of silk bolting cloth used for oceanographical nets (p. 216). The third group, the nannoplankton, consists of all the most minute forms which pass through the meshes of a net of this type. They must be taken with nets of even finer silk (cheesecloth) or separated from the water by means of a centrifuge. This, like the classification into plankton, nekton and benthos, is a crude and arbitrary system. Very many orders and families have members in both the micro- and macroplankton and there are, of course, many animals which begin life as micro- or nannoplankton and grow into a larger class as they develop.

Most of the smaller members of the plant plankton (many of the diatoms, the dinoflagellates and coccolithophores) may be classed among the nannoplankton. So may such bacteria as exist in the upper layers and the smaller Protozoa. All the rest, both plant and animal, must be classed as either micro- or macroplankton. Of these two groups the former is by far the larger. The large plankton animals are comparatively few and there are no plants that fall within the macroplankton.

Many plankton animals spend all their lives drifting between the surface and the bottom either inshore or far out in the open ocean hundreds of miles from land. They never have any relation to a substratum at any stage of their life history from the egg to the adult. They form, therefore, a permanent floating population, quite independent of the land or of the ocean bottom. But inshore a very large part of the animal plankton consists of the young stages of creatures which spend their adult lives crawling over, or burrowing into, or fixed to the

bottom and which therefore belong properly to the benthos. There are also the helpless drifting fry of fish which belong to the nekton. These we may call the temporary plankton since eventually they will settle on the bottom or change into actively swimming fish or else perish.

We must deal with the permanent plankton first and of these, so that we may begin with the lowliest forms, we must first take the microscopic single-celled creatures belonging to the great group of the Protozoa. In spite of their humble position at the bottom of the evolutionary ladder and the fact that their bodies are made o only a single cell, many of the planktonic Protozoa are extremely complicated in structure and of very great beauty. Many are microscopic but some are just large enough to be seen with a hand lens. It is only under the microscope, however, that their true beauty and fantastic form can be seen. The most important orders of Protozoa in the plankton are the Foraminifera and the Radiolaria, both of which are most abundant in warmer seas though there are many which live in temperate waters.

The Foraminifera (Fig. 5)—the hole-bearers as their name implies—are enclosed in skeletons, usually of lime, divided into separate communicating chambers and built on some sort of spiral plan. The outside of the skeleton or shell is pierced by innumerable fine holes through which radiating filaments of protoplasm stream out into the surrounding sea water. Sometimes there are stiff radiating spines, part of the skeletal structure, which support a protoplasmic foam around the central shell within. Food particles become entangled among the threads and ingested by the coalescence of several

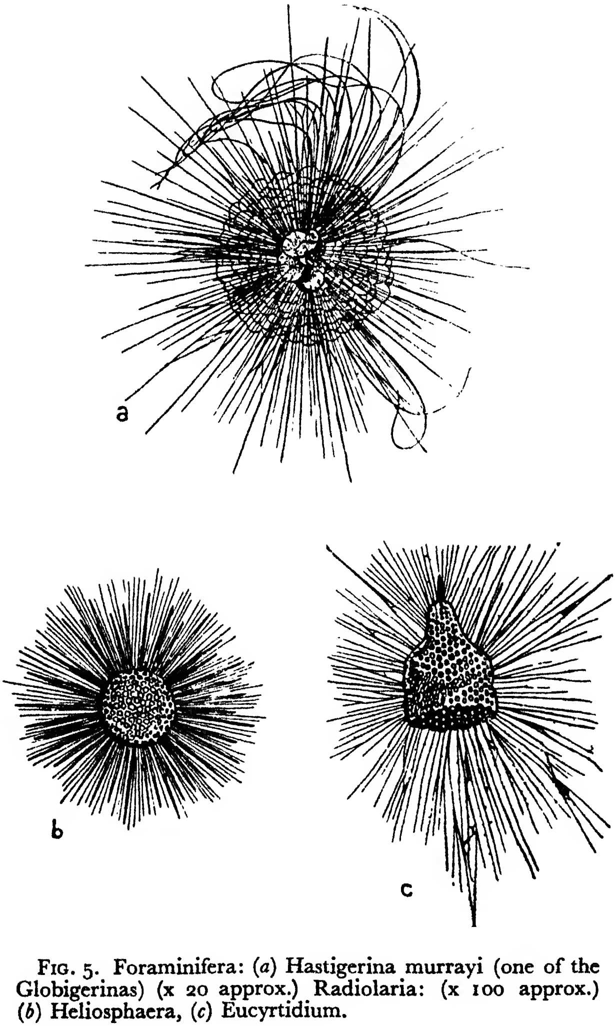

Fig. 5. Foraminifera: (*a*) Hastigerina murrayi (one of the Globigerinas) (x 20 approx.) Radiolaria: (x 100 approx.) (*b*) Heliosphaera, (*c*) Eucyrtidium.

neighbouring threads around them to form a little island of engulfing protoplasm at the junction.

The Radiolaria (Fig. 5) have skeletons of glass (silica) like those of the diatoms but of even more intricate design. The skeleton may be a basket-work sphere or several such spheres, one inside the other like a Chinese ivory ball, or it may be a little urn or a vase fashioned from an exquisitely delicate basket work of silica. Many have radiating spines while others have only the spines but no other skeleton at all. All, however, have fine radiating protoplasmic threads which entrap food particles like those of the Foraminifera.

The significance of these fantastic creatures, apart from their astonishing beauty, lies in the fact that thousands of square miles of the ocean bottom consists largely of their accumulated skeletal remains. One of the Foraminifera, the genus *Globigerina*, with its little many-chambered shell, forms by far the largest proportion of the calcareous ooze covering large patches of the bottom of the Atlantic Ocean. Many of the sedimentary rocks, notably the chalk, are made of the fossil remains of Foraminifera and are classified according to the species they contain.

But these minute forms and many others taken with them by the finest silk nets can only be seen if the plankton sample is examined closely in small fractions at a time under the microscope. If a silk net is towed through the water of, say, the English Channel for a quarter of an hour the catch, which collects in the metal bucket at the bottom of the net, looks to the naked eye like a multitude of little rods and seeds. They appear at first sight more vegetable than animal. If emptied into a glass vessel they can be seen jerking and hovering in the

water with little darting movements apparently at random. If you darken the room and stir the plankton in the jar with a pencil a shower of pale bluish sparks will flash for an instant in the water, for very many of these creatures have the power of giving out light from various parts of the body when stimulated. Much of the glitter and sparkle of the sea foam at night is due to their presence. If you pour a little formalin into the water they become furiously agitated, dart in all directions, giving forth their diminutive fires and, in a few seconds, become motionless and sink to the bottom of the jar growing slowly opaque.

It can be seen now that the catch consists for the most part of certain kinds of animals which dominate all the others in the micro- and macroplankton. Some 70 per cent. of the sample will be made up of creatures which at first sight look like hay-seeds or grains of wheat. Now that they are still they can be seen to be very small crustacea with a rounded or oval fore part and a jointed hinder part. They have a pair of long antennae and four or five pairs of blade-like legs beneath the oval fore part of the body. Each pair of legs is joined across the base so that the two limbs beat backwards together like a pair of oars and because of this they are known as the oar-footed crustacea—the Copepoda. With their oar-like legs and their long antennae they row themselves in spasmodic jerks through the water.

The copepods (Fig. 6*a*) form one of the dominant and most numerous groups in the animal plankton. A single haul of a quarter of an hour in the Channel during the early summer may bring up as many as a quarter of a million copepods of various sizes, enough to fill a couple of two-pound jars. Their range of size is very

great for some are microscopic when fully grown while many are the size of large wheat grains and others are larger still, three or four millimetres in length. The larger forms, especially in the tropics, are strikingly beautiful with long red or bronze fringes on their antennae or glittering metallic colours (*Sapphirina*). Round the coast of Europe one of the most important copepods is the Calanus (*Calanus finmarchicus*), sometimes known as 'brit'. It is the food of the herring and of certain whales and forms dense shoals in northern inshore waters off the coast of the British Isles and Norway. The herring or the whales swim through these shoals engulfing the copepods in thousands and as many as 6,000 Calanus may be found in each herring. It has been found that the herring catches are always largest where the swarms of Calanus are thickest. The copepods, since they make up so large a proportion of the plankton, form the food of many of the larger animals of the plankton and of many plankton-feeding sea birds. Petrels, such as the wandering albatross or the stormy petrel, which feed on plankton in the open ocean, carry in their crops a pulpy mess which consists, inevitably, largely of copepods.

The copepods, however, occupy an important position in the plankton quite distinct from the part they play in the diet of fish, whales and birds. They themselves feed mainly on diatoms and nannoplankton. And since they occur in vast numbers and are extraordinarily voracious they are the chief grazers upon the ocean meadows. It has been calculated that a single copepod eats half its own weight of diatoms in a day. One can scarcely imagine a horse or a cow that ate half its own weight of grass or hay every day.

Besides the seed-like copepods in our sample of plankton there are sure to be a great many elongated transparent creatures rather like threads or rods. Some may resemble hairs not much more than three or four millimetres in length but others may be several inches long and have the diameter of a pencil. These are the arrow worms (Chaetognatha) (Fig. 6*b*). Their name means 'spiny jaws' and on closer examination it can be seen that each thread has a knob at one end which is the head. This is armed with rows of sickle-shaped spines arranged around a mouth with several horny teeth. A pair of stabilizing fins and an aileron tail give these creatures—they are not really worms at all—an exceedingly formidable appearance and a shape most excellently suited for the swift pursuit of prey—a minute submarine torpedo with grappling hooks. It is chiefly the savage voracity of these tiny marauders of the open ocean that gives to the arrow worms their importance as members of the animal plankton. They occur in swarms which are often only slightly smaller than those of the copepods and they feed mainly on other animals in the plankton, chiefly the smaller copepods, which they seize and devour with their powerful jaws and spines. It is not unusual to find an arrow worm with a copepod in its stomach almost as large as its own head. The arrow worms, in fact, are primarily grazers on the copepods and other plankton animals which in their turn graze upon the diatoms.

The sample may also contain creatures like small shrimps. They will probably be less numerous than the copepods but are on occasion more numerous than the arrow worms. In the Southern Ocean it sometimes happens that swarms of these creatures are found to the

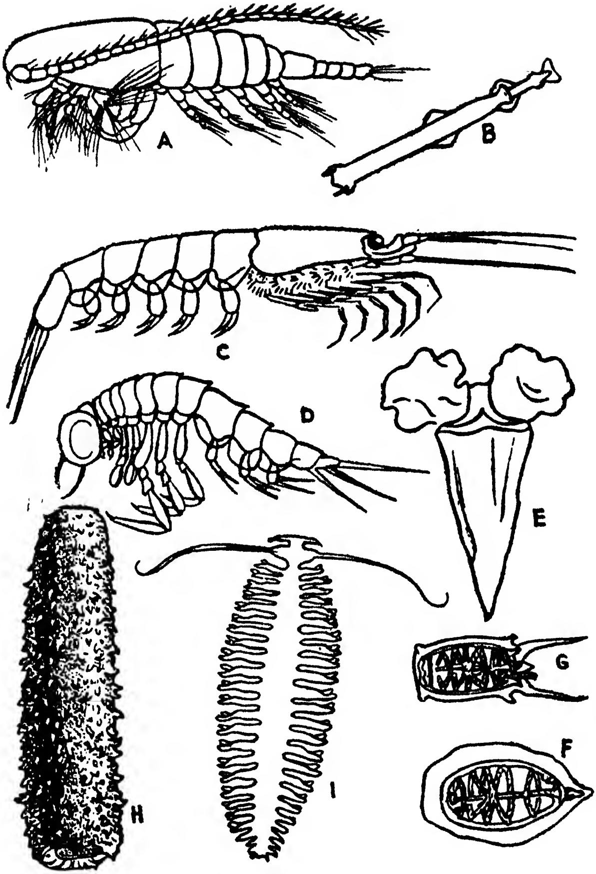

FIG. 6. Animals of the plankton: (*a*) Calanus (x 12 approx.), (*b*) Sagitta (x $\frac{1}{2}$ approx.), (*c*) Euphausia superba (x approx.), (*d*) Parathemisto (x 2 approx.), (*e*) A pteropod (x $\frac{3}{2}$ approx.), (*f*) Salpa—the sexual form (x $\frac{1}{3}$ approx.), (*g*) Salpa—the budding form with a chain of little salps hanging out (x $\frac{1}{3}$ approx.), (*h*) Pyrosoma (x $\frac{1}{6}$ approx.), (*i*) Tomopteris (x $\frac{1}{2}$ approx.).

exclusion of all other animals. These are the euphausiids (Fig. 6*c*), which are not shrimps in spite of their appearance, for they have forked swimming legs beneath the fore part of the body while shrimps have single undivided legs. Their importance in the plankton lies in the fact that they sometimes form the sole food of other animals, especially whales and birds. In the Southern Ocean along the edge of the pack ice a large euphausiid (*Euphausia superba*), which may be some two inches long when full grown, forms dense shoals which can be seen drifting like reddish clouds in the water. This is the krill, which forms the exclusive diet of the great commercial whales of the Antarctic. During the southern summer the whales browse on these shoals of krill, engulfing them in millions in their capacious mouths and filtering them from the water with the horny whalebone plates that hang down from the upper jaw. Penguins in the Antarctic also feed on krill and so—contrary to what one might suppose—do the so-called crab-eater seals. Most of the euphausiids in northern waters are very much smaller than the krill but one of them (*Nyctiphanes*) drifts in shoals off the coast of Norway, where it is the northern counterpart of the southern krill and sometimes forms the food of whales. All the euphausiids have beautifully developed light organs, each with its own lens and reflector, in various parts of the body and much of the sparkle and glitter of the plankton is due to them.

A plankton sample taken in the North or South Atlantic will be sure to contain at least some and very often immense numbers of a brownish spidery crustacean belonging to the same order as the sand-hoppers, with a big head and a laterally compressed jointed body

(*Parathemisto*—Fig. 6*d*). It has one pair of legs bent into an elbow and very much longer than the others and a widely splayed fan-shaped tail. This creature, of the sand-flea or sand-hopper order (Amphipoda), is extremely abundant in temperate seas and, around South Georgia in the South Atlantic, it often forms dense shoals. Like the arrow worms these are most rapacious beasts and feed on other members of the plankton. Perhaps we should mention too another member of the sand-hopper family, common in all the seas of the world though never forming shoals, the strange *Phronima*, which makes a house out of the dead cellulose cases of planktonic sea squirts, the salps, which we shall notice presently. In these transparent glassy barrels the little crustacean is carried about the ocean free of charge, as it were, without any effort at all.

All these animals, and others beside them which we have not space to mention, belong to the micro- and macroplankton and are caught in large numbers in almost any haul with fine silk or with canvas nets in temperate waters. Sometimes one group or other forms dense shoals which almost exclude the presence of any other group. All plankton animals of whatever size have a tendency to form shoals. The reasons for this are probably purely mechanical. In the open sea animals which have been spawned together tend to remain drifting together and the action of wind and waves tends to collect them into droves, very much, perhaps, as ice floes become collected into droves upon the surface. It therefore sometimes happens that in one place the net may bring up thousands of one particular animal—possibly to the exclusion of all else—while a few miles farther on not one may be taken. Many of these shoaling

animals, the copepods and the krill, form the staple diet of whales or fish or birds and all of them are grazers upon the diatom crops or on the macroplankton or on both. Therefore these creatures occupy an important intermediate position in the economy of the sea—the central links of a natural chain leading from the diatoms up to man himself. But there is a certain number of animals of the plankton which are very much larger than those we have so far mentioned. These are the larger members of the macroplankton. Firstly there are the sea butterflies. These are molluscs (Pteropoda) (Fig. 6*e*) with a fine lime shell of paper-like delicacy, sometimes conical or triangular and sometimes curled in a tight spiral like a snail. They may be not much larger than fine shot or the shell may form a frail and delicate pyramid an inch from base to apex. The mantle edge is produced into wings with which the creature flaps through the water, as the name implies, like a butterfly. They are common in all temperate seas and form the food of fish but are apt to occur suddenly and quite locally in millions and in certain isolated patches of the North and South Atlantic the bottom consists of ooze made of their remains.

Secondly, there are the sea squirts. Sometimes for days together the sea will be found to be populated by little else but these of one kind or another. The commonest are the salps, which (Fig. 6*f* and *g*) look like shapeless lumps of jelly with a soft knob the size of a small cherry embedded in one end of each. The bag of jelly consists of a cellulose case containing a sac with walls built on the pattern of a sieve. Water flows into the sac through an aperture at one end of the case, through the sieve-like walls of the sac and out through another aperture at the

side of the case. The sieve strains out food particles (diatoms, coccolithophores, &c.) which are carried to a central groove by fine hairs (cilia) and backwards along the groove to the creature's viscera, the round hard object like a cherry at the base of the gelatinous case. The squirts have hardly any power of movement at all, except such as may be imparted to them by the continuous gentle flow of water through them. They simply drift helplessly, often in gigantic numbers, and one encounters them suddenly for no apparent reason, millions upon millions of inert lumps of jelly which clog and even break by their passive weight any but the heaviest and largest nets. The salps reproduce in the summer at a very great speed by means of what is known as alternation of generations. This involves a sexual generation producing eggs from which hatch individuals that reproduce asexually by budding or perhaps by fission. This is a common manner of reproduction in many invertebrate animals but is quite unknown among the vertebrates. It is found among the lower forms, such as the Protozoa, developed to an extreme of complication and refinement, as it is also among the parasitic flatworms. Among insects it is found among the aphids (greenfly). In the sea we see it in the jelly-fish and sponges as well as in the salps. It may be looked upon really as a way of gaining quick reproduction and dispersal while conditions for growth are good, while food or light or air are abundant. It is a time saving device but it is like a high income tax—it cannot go on forever. It is an expensive process and in the end a reckoning comes as a weakening or degeneration of the stock. Then the sexual process must take place in order to restore the spent vigour of the race. Among the salps the individual

that develops from the egg buds off hundreds of daughter salps from a process of its own body, the stolon (Fig. 6*g*). These individuals produce the eggs which are fertilized in the water and grow into further stolon budding individuals. In this way the shoals very quickly multiply and extend for hundreds of miles.

Another kind of squirt which is often met with drifting in countless numbers in the sea, clogging nets and hampering gear, is the fire body or Pyrosoma (Fig. 6*h*). If you gaze down at night over the side of the ship you may often see beneath the surface large luminous bodies which do not twinkle and flash but make a steady glow. Many of these are caused by Pyrosoma, large colonies of small salps. Each colony is shaped like a long gelatinous dunce's cap, some when quite young no bigger than a thimble, but others of all sizes up to a length of three or four feet. When old they tend to become flattened and some indeed are always strap-like and slimy, covering nets and other animals with which they come into contact with an exudation like a sticky saliva. Other Pyrosoma colonies, again are long and ropy. Each of these colonies has an opening at one end leading into a cavity inside the hollow tube around which thousands of miniature salps are arranged, embedded in a foundation of jelly. Their mouths point outwards all around the exterior of the colony and each has its own sieve-like sac, the exit of which leads into the central cavity of the tube. The water is therefore drawn into the colony through the walls of the tube by the individuals which compose it and driven out through the communal opening. The colonies have perhaps a very slight power of movement caused by the stream of water they expel through their mouths but in the main they, too, drift helplessly. They

are remarkable for the brilliant phosphoresence they give out as each minute salp in the colony lights up independently on being stimulated until the whole gelatinous cone seems to glow with a dim incandescence. If a large Pyrosoma is placed in a dish in the dark it is possible to write one's name on its surface with the finger, for each individual shines when touched by the finger and continues to glow for some seconds afterwards.

Various kinds of jelly-fish, both great and small, are abundant in all the seas of the world. Though they are often present in countless thousands in the water quite locally they seldom form dense compact shoals like the salps or the sea butterflies. Around the fjords of Iceland large red jelly-fish (*Cyanea*) may be seen in myriads, pulsing slowly through the water trailing their long stinging tentacles. They are voracious plankton eaters and it is perhaps for this reason that the fishermen say that the fishing will be poor if 'sluthers'—jelly-fish—are abundant in the spring.

The jelly-fish show alternation of generations in their reproduction—that is, a sexual form producing eggs and sperm which in turn give rise to some other form which can reproduce asexually and repeatedly. The smallest jelly-fish in our waters are the sexual swimming bells produced by branching colonies of polyps which live attached to rocks or weed. The large jelly-fish like *Cyanea* are sexual stages budded off from single small polyps growing on the bottom.

We must mention, perhaps, the Ctenophora or comb-bearers—large oval globes of jelly which swim by means of rows of vibratile filaments arranged meridionally. They, like the Pyrosoma, give out a brilliant phosphorescent glow and it is they which cause many of the large

luminous globes and spheres which can be seen beneath the surface from the side of the ship. Like the jelly-fish they are voracious plankton feeders. Then there are the 'Portuguese men o' war' with their inflated swimming bladders resting on the surface and bunches of variously modified persons or individuals, for these are colonial associations of polyps in which there is a strict division of labour and some of the individuals are tactile, some digestive, some reproductive and some, the long trailing tentacles, offensive. Another colonial polyp is the 'By-the-wind-sailer' which has the form of a minute raft, a circular disc an inch or so in diameter with a small vertical sail above which catches the wind and drives the little boat over the surface. The individuals, clustered beneath the raft, are, again, variously modified for the digestive, tactile or reproductive function.

Lastly there are a few worms among the plankton which occasionally occur locally in vast numbers. The most common one is the exquisite, almost transparent, *Tomopteris* (Fig. 6*i*) with its forked lateral arms like the teeth of a double comb. It wriggles through the water with a wavy motion. The palolo worms swarm in the tropics, mainly around the Pacific Islands at certain states of the moon and shed certain sections of their bodies which bear the sex glands. But they hardly count as members of the plankton for they spend the greater part of their lives upon the bottom.

The animals which have been briefly described above, and many others besides, belong to the permanent plankton. They spend the whole of their lives, from the egg to the adult, adrift and independent of the shore or of any substratum. They are the perpetually floating population of the ocean. But every year, in the spring

and early summer, the plankton is greatly increased by the addition of a temporary floating population. It consists of the minute larvae and young stages of a whole host of animals which in adult life belong to the benthos. In addition there are the planktonic fry and young stages of many kinds of fish.

Only in water, in a fluid and moving medium, is it possible for animals to remain rooted to one spot like the sea anemone or to live permanently in a tunnel like a burrowing worm. For such a way of living entails the loss of that primary characteristic of animal life, the power to chase and capture food. In moving water the animal may remain fixed and the food may be carried to its door. Yet the problem of dispersal remains. If fixed animals repeatedly reproduced themselves in the same spot it would not be long before there was no more room. Creeping and burrowing animals too are faced with the same problem—that of living space. In order to overcome this difficulty a very large number of animals of the benthos spend their youth among the plankton. They may have young forms, larvae, which are utterly unlike the grown animal and which drift free upon the currents and tides. Many of these have some power of swimming but as a rule they are too feeble to resist the forces that sweep them out to sea or far along the shore or into the mouths of rivers. As an example, for there are far too many to quote them all, we may take the shore crab which starts life as a minute spiny larva (Fig. 7*b*) called the zoaea. This hatches from the egg in shallow waters in the spring and, after passing through several different stages, settles down upon the bottom and changes into the adult. Again, the oyster starts life as the spat (Fig. 7*a*), a microscopic transparent creature

which swarms above the oyster bed, keeping itself in motion by means of a fringe of fine vibratile filaments. The spat settle down in due course upon a hard substratum and change into oysters. The common barnacle, that covers the rocks between the tide marks, emits clouds of minute triangular larvae in the spring. These

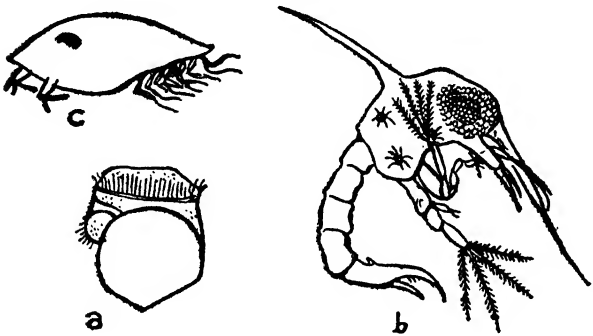

FIG. 7. (*a*) Oyster spat (x 20 approx.). (*b*) Zoaea larva of shore crab (x 20 approx.). (*c*) Cypris larva of common barnacle (x 15 approx.),

change into a bivalved form which looks at first sight like a little mussel (Fig. 7*c*). It cements itself to a rock by one end and turns into a barnacle, a little shrimp-like creature in a box made of plates of lime, standing on its head and kicking food into its mouth with its legs. The bristle-worm starts life as a microscopic globe of jelly called the trochophore—the ring bearer—because of the circlet of vibratile hairs it carries round its equator. These give it a feeble motion through the water as do those of the oyster spat. While still drifting in the upper

layers it begins to push out a segmented tubular body from its downward pole and presently settles down upon the bottom and grows into the adult worm—sloughing from its head the remains of the trochophore and its ring. As a last example, though a chapter could be filled with them, we may take the sedentary bottle squirt. This is a cousin of the floating salps of the plankton and resembles a bottle with two necks, sucking water in at one and blowing it out at the other. It starts life as a tadpole with a gelatinous stiffening rod along its back which is looked upon as the forerunner of the backbone of the vertebrates. When the tadpole settles down it becomes fixed to the substratum by its chin, loses the stiffening rod and turns into the bottle which spends the rest of its life siphoning water through its body and bears no resemblance to a vertebrate animal at all.

These are only a few examples of the many animals of the benthos which bring about the necessary spread of their species by living free in the upper layers during the early part of their lives. Added to them there are most of the food fishes which live upon the banks and are classed as nekton—the cod, the ling, the haddock, the whiting, the plaice and sole—as well as the shoal fishes—the herring and the mackerel. All these have young fry which drift helplessly among the plankton and so achieve dispersal.

But a planktonic youth is not the only means of dispersal which animals can adopt. There is the method of alternating generations which we saw in the salps and the jelly-fish. This is a quick way of dispersing the species while conditions are favourable but it reduces the vigour of the race and must in due course be supplemented by the sexual process.

Now life in the sea is full of hazards and it follows that such methods of dispersal are exceedingly wasteful. The young forms and larvae drift out to sea in millions and come to nothing because they fail to find any substratum to settle on when they reach the appropriate stage in their growth. More millions are devoured by hosts of other animals. Others are washed ashore and dried up and who knows what other accidents may befall helpless delicate drifting creatures in the wide ocean? It follows then that only a very small proportion indeed of the eggs that are spawned will hatch into young forms or larvae and of those only a very small fraction has any chance of eventually becoming a grown animal. Yet when one beholds the incredible multitude of barnacles or mussels upon the rocks, or lugworms in the sand, and considers that each is the fortunate survivor among thousands that have perished, one realizes dimly the immense fecundity of animals in the sea—especially the benthos animals and the many fish which leave their eggs and young fry to the chances and perils of the open sea. The edible oyster produces 1,800,000 eggs at a spawning—but only a small fraction of the vast cloud of spat can settle down and become oysters. Not only have they many natural enemies but they must find exactly the right kind of substratum, clean and hard, to settle on. Mud or sand or stones overgrown with weed will not do. If they do not find the right substratum at the critical time of their lives when they are ready to settle they die. The common sea-slug (*Doris tuberculata*) lays a spiral coil of jelly in which six or seven hundred thousand eggs may be embedded. Among the fish the cod sheds between four and six million eggs at a spawning. If all were hatched and grew into full grown fish, in a few years all the sea

of the world would be packed with codfish like sardines in a tin. One may take it that the number of eggs laid by a marine animal is a measure of the hazards the creature has to meet and survive in order to become an adult rather than a measure of the abundance of the species.

The vast majority of the animals of the benthos and of the fishes live in shallow water, mainly on the continental shelf. This is because the inshore waters are the richest in the plant life on which the young forms feed and because no suitable substratum is available in the open ocean. The temporary plankton is therefore found mainly inshore, though not entirely since certain larvae, like the Phyllosoma larva of the rock lobster (*Scyllarus*) (Fig. 3) and the Leptocephalus larva of the eel, are found habitually in the open ocean. Many hundreds of creatures which belong to the temporary plankton are bound, of course, to be swept out to sea but these will perish. All around our shores, therefore, a vast cloud of minute and hopeful young life rises into the luminous waters every spring, adding itself to the permanent floating population whose home is the vast ocean. During the summer these young forms die in millions but a small fraction grows to maturity, enough to people with abundant life our crowded shores and sandbanks.

CHAPTER IV

THE OPEN OCEAN

Diatoms as primary producers—Biological chains in the sea—The fertility of the sea—The seasonal cycle of the plankton—The thermocline—Distribution of the plankton—Form and colour in the tropics—Influence of temperature on distribution—The neritic zone—Plankton and water masses—Diurnal vertical migration—Seasonal vertical migration—Bipolarity—General life history of plankton animals.

THE DIATOMS are the foundation upon which, ultimately, the whole structure of ocean economy rests. In the same way the well-being of our human society rests basically upon the green vegetation which clothes the earth and is the food of the animals whose meat we eat. The diatoms form by far the largest proportion of the plant plankton, the grasslands of the ocean, upon which the animals of the plankton feed. In addition to the diatoms we must include among the primary producers of the sea a multitudinous secondary plant life some of which, the dinoflagellates and Coccolithophoridae, we have already briefly described. The animal plankton grazes ceaselessly upon this profuse vegetable life, for all the smaller animals of both the permanent and temporary plankton feed mainly, sometimes entirely, upon diatoms and other forms of microscopic plants. The larger plankton animals feed voraciously upon the smaller and so, upon this green foundation, are built up the many biological chains of mutually dependent creatures—delicately balanced and minutely adjusted

in the sea as upon the land. At the head of many such chains stands mankind whose harvest of fish and whales from the ocean is dependent on the complicated relationships of many forms of life and of many physical factors. In the Southern Ocean the whales feed on the krill, *Euphausia superba.* The krill in turn feed on the great diatom crop which bursts into green life in those waters in the spring. But the diatoms themselves are grazed upon by the teeming animal plankton—the copepods, the arrow worms, the salps, the other euphausiids and very many other small creatures. These are, in turn, the food of a host of sea birds, larger plankton animals and fish. Again, cn the northern fishing banks the worms and molluscs, on which the cod and haddock feed, start life as larvae, members of the temporary plankton, which are dependent on the spring diatom crop. They in turn are eaten by the larger plankton animals, arrow worms and jelly-fish—the sluthers—which by their abundance do serious damage indirectly to the fishing grounds. The young fish fry themselves are feeders on the diatom crop, on the microplankton, including the very larvae of the molluscs and worms which will later be their food. But the fry, again, are at the mercy of the larger plankton animals and of the birds. Thus all the inhabitants of the ocean are interdependent and interrelated and at the top of the whole complicated structure stands man himself whose highly mechanized fisheries often upset the delicate balances on which their harvest depends. Sometimes the well-meaning efforts of man to assist and nurse nature in one direction react upon him in another, for the organization of life and of living communities is like a tuned engine and cannot be interfered with except at a risk of throwing it out of adjustment.

When Holy Island, for instance, off the coast of Northumberland, was made a sanctuary for sea birds, the birds increased in numbers so that the whelks and cockles and other molluscs on the shore were devoured in such quantities that the plaice and other flat-fish, which also fed on them, were unable to find enough food and the inshore flat-fishing declined. Brave and hardy people on the north-east coast of England suffered accordingly. Among the plankton, however, these natural balances are less easily upset by artificial agencies. Yet the supply of animal and vegetable food in the sea is not inexhaustible for natural causes set limits to its abundance.

The spring is the time for an outburst of life in the sea as profuse and triumphant as that which takes place on land. It is heralded in the late winter months by the proliferation of the diatom crop.

Since the diatoms are plants they must have sunlight for their existence. They flourish, therefore, only in the upper layers of the water, in approximately the upper 250 feet. This is called the euphotic zone. It is the surface layer of water which, in clear tropic seas, is well lit by the sun. Below about 250 feet the sunlight penetrates less and less and the production of plant life steadily diminishes until, at about 600 feet, there is not enough light to support it. Thence down to the bottom there is total darkness and no plant life can exist. In temperate northern and southern seas, as the sunlight strengthens and returns after the long winter, the diatoms and other plants begin to increase and the crop rapidly becomes exceedingly rich. Each one of the countless diatom cells divides once every thirty-six hours. In the South Atlantic in the early summer there may in quite a short time be as many as a quarter of a million cells to a litre of

water, and silk nets, towed through this proliferating green soup, soon become choked or even split with the weight of the plant life they bring up. It has been calculated that in a normal year the annual yield of vegetable matter in the English Channel is 5½ tons per acre of water, assuming a uniform depth of 38 fathoms. With this we may compare the average yield of hay in England which is 30 cwt. per acre, while an exceptionally good year with two crops yields three to four tons per acre.

In northern waters around the British Isles the diatoms begin to increase in numbers about the end of February. By the end of March they have increased fourfold. In April a decline sets in and the crop steadily falls off to a minimum in August when it is again down to the winter level.

This sudden blooming of the ocean meadows in March is due to two causes, to the returning strength and increasing height of the sun and to the rich store of nutrient salts—phosphates and nitrates—which has accumulated in the water during the winter when, owing to the poor light and short days, there were no plants to use it up. These salts, present in the water in minute amounts, govern the abundance of plant life and so we can go one step farther back than the diatoms and say that they govern the abundance of the whole of life in the sea. More than that, they underlie those fluctuations in the fisheries, in the annual yield of herring, cod and haddock, which have so long been among the mysteries of the sea. For the diatoms are the grass of the sea and the salts the soil in which they grow. When the salts for any reason fail, the diatom crop fails also and with it all the animal plankton that grazes on it. Ultimately the

fisheries suffer too. This indeed is just what has happened in the Channel in recent years. There has been a fall in the amount of phosphate in the waters off Plymouth. Formerly Atlantic water, rich in phosphorus, brought to this area an abundant animal plankton which was the food of the winter herring harvest. In the early thirties this flood of Atlantic water ceased so that the herring fishery at Plymouth began to decline and is now almost extinct.

In April two influences begin to make themselves felt in our seas. One of these is the hatching out of vast clouds of young plankton animals following hard upon the spring outburst of plants. They swarm upon the floating fields like locusts and steadily graze them down. The second influence is the swift exhaustion by the plants themselves of the nutrient salts, the soil in which they live, and, most important, of the dissolved silica from which their delicate skeletons are built up. The result is a steady decline in the diatom crop which goes on throughout the summer until August. But after August the plant life recovers and in September blooms again to about three-quarters of its spring abundance. Two influences, again, are at work to bring about this second increase in late summer. During the summer months the surface water is warmed by the sun to a temperature two or three degrees higher than the water underneath. This means that a warmer and therefore lighter layer is formed which lies on top of colder and therefore heavier water below. The two layers are separated by a discontinuity called the thermocline. The depth at which the thermocline lies varies according to the amount of sunshine and calm weather which the summer brings. In the English Channel it lies usually at about 40 to 45

feet in May or June but a gale of wind, by churning up the water at the surface, sends it down to 58 to 60 feet. We may say that during the summer the thermocline cuts off the upper 50 to 60 feet completely from the colder water below and no mixing takes place across it. Throughout the summer months from March to August the plant life, living and multiplying in the upper layer, uses up the nutrient salts above the thermocline. As the plants and animals die they sink down and their decay restores the mineral salts, which they have been steadily withdrawing from the upper layer, to the layers below. The surface layer therefore loses salts continuously throughout the summer. The soil gets poorer and poorer and there is no replacement. The plant life therefore declines. But towards the end of August the surface layer begins to lose more heat than it gains from the sun. The temperature of the upper layer falls to that of the lower and so the thermocline breaks down. The water below now mixes with that above, renewing the nutrient salts in the surface water. Although the declining sun is losing strength now there is still enough light for photosynthesis and the diatoms begin to multiply again. But there is another factor which helps to bring about the second blooming of the diatoms and that is the death of the animals that feed on them. All over the temperate oceans the animal plankton begins to die off towards the autumn, for most of these small creatures live only one year, or at most two, and die after they have fulfilled their primary object in life, that of spawning and reproducing their kind. In late summer the parents of the generations spawned since the spring begin to die and with the onset of winter millions of their offspring perish also. They sink down, restoring by their

decay the diminishing fertility of the sea and reducing the population that grazes on the plants. In shallow inshore waters like the English Channel the temporary plankton also disappears during the course of the summer as all the millions of larvae, spawned in the spring, settle down —such as have survived the perils of their brief youth— and become adult animals fixed to the bottom or burrowing into it or crawling over it. As the grazers die the meadows of the sea become lush again, but not for very long for soon the sunlight becomes too dim and the days too short so that photosynthesis becomes impossible. In October the diatoms are already diminishing again and they decline steadily to a minimum in December.

In the southern hemisphere there is no thermocline because of the mixing processes which are constantly going on along the convergence and near the continental slope where deep cold water wells up from below. Frequent gales throughout the summer, too, keep the water stirred up so that no surface layer of warm water can form. As a result there is only one well marked outburst of plant life in the south. In the warmer waters of the Southern Ocean near the convergence it takes place in December, about midsummer, two or three months later than the corresponding time in the north. It is later still in colder southern waters where the greatest abundance does not occur until January and in the far south, in waters not uncovered by the pack ice until late spring or early summer, the blossoming of the diatom crop may be delayed until February, nearly autumn, and then must die away very quickly as the winter sets in. The southern crop declines steadily throughout the remainder of the summer and has no

second maximum comparable with the autumn recovery in northern waters.

Soon after the spring outburst of plant life, in April or May in northern waters and in December or January in the south, comes the spawning and vast proliferation of the zooplankton. In northern seas this reaches its greatest abundance in about August when the plant life has diminished to about its lowest point. The surface waters become filled with the young of copepods, arrow worms, euphausiids and many other forms in teeming millions. Inshore appear swarms of the larvae of worms, molluscs, starfish and sea-urchins. Clouds of the minute larvae of barnacles and mussels and the swimming bells of polyps drift in the creeks and gullies among the rocks. As the summer goes on, in June and July, these settle down and disappear from the plankton and farther out to sea larger animals, young fish, jelly-fish, salps, pyrosomas appear and devour the smaller forms. The population is continually changing as later spawned broods of animals take the place of the earlier ones. About the end of August the animal plankton diminishes, and then the diatoms bloom for the second time. It shows no second maximum because by September life is slowing down and winter with its rigours is approaching.

In a vast and apparently uniform environment, such as the ocean seems to be, it might be imagined that there would be little difference between the floating population of one area and that of another. But we have already seen that certain natural boundaries exist in the ocean, such as the antarctic and sub-tropical convergences, which divide the populations on either side of them as sharply as mountain chains on land. On a cruise southward over the Southern Ocean we find a very sharp

change in the kind of animals taken in the nets after passing the line, invisible but detectable by means of instruments, which we call the antarctic convergence (Fig. 2) and which divides the cold antarctic from the warmer sub-antarctic water. This is true to a greater or lesser extent of all the animals of the southern plankton and the division is sharpest where the differences in the temperature and salinity of the water on either side of the line are most pronounced and less sharp where these differences are not so marked. A similar though less definite change in the population takes place at other boundary lines such as the sub-tropical convergence. But besides these more or less sudden jumps in the character of the population we notice that there is a general and gradual change both in quantity and quality from one part of the ocean to another. Certain animals and plants are characteristic of certain seas and certain associations of animals of certain masses of water. For instance, around the British Isles the water of the Atlantic has a characteristic population which marks it from the water of the North Sea and the Channel. The greatest and most sweeping changes, however, take place from north to south roughly across the lines of latitude. As we move southward from the tropics we find that the size of the catches in our plankton nets increases very greatly. In the tropics the nets may take a few hundred animals and hardly any diatoms at all, but in the Antarctic they take hundreds of thousands of animals and uncountable millions of diatoms like thick mud in the summer. But there is an exactly opposite change in the numbers and variety of the different kinds of animals and plants. A haul with a coarse canvas net in the Antarctic may bring up ten or twenty

thousand copepods belonging to perhaps three or four species, but in the tropics the same net will bring up perhaps a couple of hundred individuals belonging to as many species. The same sort of change takes place from the tropics northwards towards the temperate latitudes, although in the North Atlantic, and to a lesser extent in the Pacific, these changes in the population tend to have a north-west to south-east direction because warm water is carried far to the north-eastward in both oceans by the Gulf Stream in the Atlantic and the Kurosiwo Current in the Pacific.

The reason for the richness of the plankton population in mere numbers of individuals in temperate waters is to be found in the inexhaustible store of those nutrient salts which nourish an abundance of plant life. Tropical waters are not nearly so rich in these nitrates and phosphates as the colder seas. In temperate and cold seas the surface is kept constantly stirred up and enriched by waves and by the rising up from below of masses of water, sunk down from the tropics and rich in salts, welling up against the coasts of the continents. But the greater variety of the population, though less numerous in individuals, in the tropics may be put down to the greater potency of life, the higher metabolic rate, of living things in warm seas. Life has a greater capacity for change on this account. It keeps taking on new aspects and evolving new shapes. It burns with a fiercer and more ardent fire.

There is another difference which we may notice between the inhabitants of cold and of warm seas. In the tropics there is a greater fantasy of form and colour. Animals which, in temperate seas, have a simple, almost functional, outline have near relations in the tropics

whose shape is greatly elaborated. Indeed the same animal may show a difference of form, an increasing elaboration, towards the tropics. The small spiny dinoflagellate *Ceratium tripos* (Fig. 3*c*), for instance, shows a progressive lengthening of its three long processes which, in the tropics, become many times their length in cold latitudes. Most plankton animals and plants, in fact, in the tropics develop elongated processes, long bristles or greatly elaborated skeletons often bizarre and, one would imagine, purposeless. They seem to be simply part of the general exuberance of life in these waters. But there is a very practical purpose which they serve. Warm water is very much less dense and, perhaps more important for minute creatures, less viscous than cold water. Its surface tension is very much lower. It therefore becomes increasingly difficult for small drifting things to keep themselves afloat as the water in which they live gets warmer. They must increase, perhaps by many times, the ratio of their surface area to their volume. And this is most effectively achieved by means of these spines, processes and fantastic shapes which at first sight appear so undirected and so wanton. They are, in fact, flotation mechanisms and assist in keeping the tiny body adrift in the thin clear waters in which it lives. In the tropics, again, we find more splendid and beautiful colours than in temperate and cold seas. In the blue and limpid waters of the tropic zone, light of some sort penetrates to a depth of more than 3,000 feet. At about 5,000 feet, however, no light penetrates at all and photographic plates exposed for two hours at this depth showed no sign at all of blackening. Animals which live within the upper 1,000 feet are either quite transparent, so that they are

invisible in the water, or else they show various exquisite shades of blue or green. The predominant note is blue and usually, as is the case in most of the fishes, the upper surface is shaded darker than the under surface. Below that depth down to about 5,000 feet the dominant note is red, often a fine crimson like the great red prawns that the nets bring up from those depths (*Notostomus*, *Sergestes*, *Acanthephyra*). The light waves of the red end of the spectrum probably do not penetrate to the depths where these creatures live but are absorbed before they get there, so that to their brethren in their half-lit world these prawns must appear black and do not become red, as it were, until they are brought up within the light of day. In the lightless depths below 5,000 feet the prevailing colour is truly black, like the small yet monstrous fishes with their gigantic mouths that live in those mysterious regions. In general the animals in the tropics show the most exquisite colourings which, alas, most quickly fade, almost before the artist can capture them on paper. In fixative they drain away completely so that when the student sees them in the museum they have assumed an unattractive straw-coloured pallor. In life there are lovely copepods such as the glittering, iridescent *Sapphirina*, like little pieces of bright metal, the deep red *Euchaeta* in the lower layers and the black *Candacia*. Often they carry fans of golden, bronze or iridescent hairs (*Euchirella*, *Oithona* and many others). The fishes are usually bright metallic silver (*Argyropelecus*) or blue like the flying fish. Altogether the fauna of the tropic seas is of a breath-taking delicacy and beauty which fades so swiftly that you might believe the sea were jealous of its treasures.

In the distribution of plankton animals the most

mportant governing factor is temperature. Every species has a higher and a lower limit of temperature and between these it lives and spawns to best advantage. Below or above these limits it cannot spawn. If the temperature is lowered the effect is to delay spawning down to a certain limit below which spawning is inhibited completely. The area of greatest abundance of an animal, however, does not necessarily correspond with the area within which it spawns, since water movements and currents may often carry the shoals far beyond the spawning limits. Some animals can live and reproduce within a very wide range of temperature but in the open ocean the range is usually narrow and covers only a few degrees. The population therefore changes steadily in aspect as we go from the tropics towards the poles.

The temperatures at which most of the diatoms flourish best lie between freezing point and 50° F. (10° C.) so that they are essentially plants of the colder waters. And this, again, is another reason for the richness of the plankton in temperate seas and its poverty in the tropics. Most animals and plants in the open ocean are also very sensitive to changes in the salinity of the water and cannot tolerate extremes outside the limits of 34 per thousand to 36 per thousand, which is about the range found in the temperate seas of the world.

As we approach the shore from the open ocean we find another change in the plankton population, both plant and animal. The shallow area above the continental shelf and within the 200 fathom line is called the 'neritic' zone. It is a region where the sea is lit by daylight down to the bottom and where the nutrient salts are more abundant because they are carried down by rivers and

washed out of the cliffs and rocks of the coast. It therefore supports a very much more abundant plant life, and hence a much richer plankton population generally, than does the open ocean. Inshore waters are the home, too, of the temporary plankton which adds itself to the permanent plankton population each spring and settles down or fades away during the summer. The neritic zone is a region of very fluctuating conditions. Near the coast the sea is liable to dilution by rivers and by drainage from the land so that the salinity is often lower and more variable than in the open ocean. The temperature of the water, too, is apt to vary close inshore, over sandbanks or over stretches of rock exposed at low water or near estuaries. Plants and animals that live in the neritic zone consequently have to be able to tolerate much greater changes in these important factors in their lives than are encountered farther out to sea. They may also have to withstand changes of acidity or of the chemical constitution of the water. For these reasons the neritic zone supports a peculiar population of its own. Many of the plants and animals of the neritic plankton can only live close inshore and die when they are swept out to sea. Some oceanic creatures die if they drift close inshore but in general the open ocean plankton invades the neritic zone and increases the abundance of life in shallow seas.

In the south this difference between the inshore waters and the open ocean is very much less evident than in the north, because the West Wind Drift, supplemented by cold masses of water welling up from below along the Antarctic continental slope, carries the inshore influences, especially the richness of the nutrient salts, far out into the Southern Ocean.

The interplay of all these factors—temperature, salinity, chemical constitution of the water—distinguishes the various water masses of the ocean one from another. It is these influences which make some waters suitable for certain animals and plants or associations of them and unsuitable for others. At the entrance to our own English Channel, for instance, there are three different kinds of water. There is the water from the Atlantic Ocean, which is warm, highly saline and rich in phosphates. It swirls round anti-clockwise south of Ireland and sometimes fills the Channel mouth. There is a tongue of water from the Bay of Biscay, warmer and more saline still, which creeps into the entrance to the Channel round Ushant and the coast of Brittany. And then there is the inshore water of the English Channel and North Sea which is different again. It is cold, not so saline and poor in phosphates. Each of these three different kinds of water has a population so distinctive in the aggregate that the untrained eye can tell them apart at a glance. The Atlantic water carries a rich population containing very great numbers of a certain arrow worm, *Sagitta elegans*. Channel water carries a sparse population of which the most important member is a very much smaller arrow worm, *Sagitta setosa*. Biscay water, on the other hand, has a population of intermediate richness and the two arrow worms are absent or almost so. It contains, however, great numbers of a copepod, *Euchaeta hebes*, and of the dinoflagellate, *Noctiluca*. So characteristic and distinctive are these populations that their major constituents can be used to indicate the kind of water in which they live as precisely as the thermometer and water sample bottle.

Some areas of the sea, again, are regions of mixing,

flooded by different kinds of water at different times so that the population varies accordingly. The North Sea is an excellent example of this for it receives two influxes of water from the Atlantic Ocean—one from the Channel through the Straits of Dover and one round the north coast of Scotland. In some years the North Sea receives more water through the Channel than round the north of Scotland. In other years the reverse is true. There seems to be a regular pulse every year, water flowing strongly up through the Channel in the spring and then slowly retreating before the counter-influence of the pulse round the north of Scotland. Now the water that sweeps into the Channel from the Atlantic, as we have already said, brings in a rich and quite distinctive population with great numbers of the arrow worm, *S. elegans*. But when the flow round the north of Scotland is strong the water in the Channel is poor in phosphate and has a low salinity. The plankton population is sparse and the Atlantic animals are absent. *Sagitta elegans* is replaced by *S. setosa* and great masses of a particular species of diatom, *Rhizosolenia styliformis*, appear on the Dogger Bank. It has been found that when this diatom is abundant in the North Sea the herring avoid the Dogger Bank and the catches landed at Lowestoft and Yarmouth are poor. It becomes possible then for biologists at Plymouth to foretell whether the east coast fishery will be good or bad by the appearance or absence of the arrow worm, *S. setosa*, in their waters. Of recent years, since about 1931, the flood of Atlantic water into the Channel from the west has weakened and the Plymouth herring fishery, which is related in some way to this water, has almost disappeared.

Thus far we have been thinking only in terms of the

horizontal distribution of the floating population. Yet the sea, unlike the land, is a realm of life in two planes so that its inhabitants can have a vertical as well as a horizontal extent. There are, indeed, no depths of the ocean where there is not some life, however slight. But we find that nearly all animals and plants have a certain range of depth which they inhabit, and within that range there is usually a smaller one which they prefer. More than that, we find that the depth at which an animal prefers to live may vary according to the time of day, the time of year and to the age of the animal itself. For instance, in the Antarctic during the summer months—for winter brings in a different set of conditions—there are certain copepods which are always in the upper layers above 300 feet (100 m.) and others which are always taken below that level. Within the upper layer there are some that are taken always in the greatest numbers between 150 feet (50 m.) and the surface and in the deep layer others which are always found between 1,500 feet (500 m.) and about 750 feet (250 m.).

There are, however, very great differences between the populations of the various layers during the night and during the day. If we make a haul in the surface layer at night during the summer we find the water teeming with life but in the daytime the net will bring in very much less, for the surface layer is almost empty. This is because the majority of plankton animals live in the surface layers at night and then sink down into deeper water when dawn comes and the daylight strengthens. They rise again to the surface after sundown. It is for this reason that the herring drifters shoot their nets at night when the fish are near the surface feeding on the plankton. The herring food, indeed,

(*Calanus*) carries out these daily mass journeys to the surface and back again with great regularity and precision and its behaviour may be taken as a general example of that of the plankton population as a whole.

In the English Channel the Calanus are to be found in by far the greatest numbers just below the surface about four or five hours after sunset. Thereafter they slowly sink, until at dawn the greatest numbers are at a depth of about 120 feet. Three or four hours after dawn they have sunk further still to about 200–300 feet, after which they begin to rise slowly to the surface again. But there are many animals, especially in the open ocean, which live at greater depths than this during the day. Some, like the mysid prawns, live on the bottom. Many of these rise towards the surface at night but may not reach it either because the night is too short and they have not time or because their powers of swimming are not great enough or because the stimulus, whatever it may be, which urges them upward is not strong enough. But the effect of all these creatures rising from below is that about four or five hours after sunset, when they reach the top of their ascent, the water is more thickly and uniformly filled with life over a much deeper extent from the surface downwards than at any other time during the twenty-four hours. Not all plankton animals make this daily journey up and down again, nor do all those that do so carry out a rise and fall of the same extent. Some make daily journeys of two or three hundred feet and others of only fifty feet or so. Further, the same animal may make longer vertical journeys the older it grows. The young stages of Calanus hardly make any vertical migrations at all and remain always near the surface, but as they grow older their vertical movements become

more pronounced and the female adult makes the most regular and precise migrations of all. The general effect, however, is that the surface layers of the temperate summer sea down to about 30 feet are almost empty in daylight but full of abundant life at night, with its greatest richness about four hours after sunset.

As great as the contrast between night and day is that between summer and winter. The plankton is very rich in summer within the surface 300 feet (100 m.) and migrates up and down from day to night largely in that layer. But as the winter comes on it retreats from the surface to levels somewhere between 800 feet (250 m.) and 1,600 feet (500 m.). Here during the winter months we find the remains of the summer abundance much diminished. The population, indeed, is only a shadow of that which filled the surface layers in the summer. At midsummer, in the waters of the West Wind Drift around South Georgia, half an hour's haul with a coarse canvas net in the surface layer at night might bring up twenty or thirty thousand of the common copepod *Rhincalanus gigas*. But at midwinter only a few hundred can be gathered from the deep layers and none at all at the surface. The same is true of the arrow worms and of all the important members of the plankton.

The reason for the general shrinkage of the population of the sea in winter is plain enough. Most plankton animals do not last more than a year or two at most. They may spawn one or more than one generation during the summer but after the spawning the parent generation dies. Those of their offspring that last over the winter are the lucky ones that successfully survive many perils, the ferocious grazing of a host of enemies throughout the summer, the action of currents and water

movements that sweep them into unfavourable areas, the failure of their plant food in late summer and the onset of inclement conditions and the increasing cold of the water as winter sets in.

When the spring comes the diminished plankton rises into the upper layers again, poor in quantity in the early weeks but proliferating more and more abundantly as the season advances and young broods of all the various animals appear as the result of the spring spawning.

What is the reason for these daily and seasonal vertical movements of the plankton population? It seems that temperature and light intensity are the two most important influences at work. Both of them act together, but one is usually more powerful in its effect than the other. Added to them is the important influence of gravity—the tendency of all plants and animals, which are heavier than water, to sink in it. Indeed the life of a plankton plant or animal is a continual struggle against this tendency and in the tropics, as we have seen, special arrangements are necessary to overcome it.

For every creature there is a most suitable light intensity which it tends to seek and each is more abundant where that light intensity exists. Plants, because they live by photosynthesis, live in the euphotic layer, the upper 250 feet which is brightly lit by the sun, but even so, different diatoms have a preference for different light intensities and flourish best at levels where they occur. It has been suggested that it is rather the change of intensity to which an animal responds than the light itself and that this acts by altering the animal's response to gravity. The normal response is downwards and the animal actively swims downwards when the light from above is bright. When the animal gets into the lower

layers the light from above grows dimmer and the tendency to swim downwards in response to gravity becomes less compelling so that the population becomes bunched together at a certain level. As the light from above begins to fade away altogether the response to gravity changes to a completely negative one and the animal begins to swim actively upward. It is certain, however, that whatever influence it is that is at work, it acts differently not only on different kinds of plankton animals but on animals of different ages since the young forms do not, as a rule, make these daily journeys up and down but are always found at the surface. Further the stimulus, whatever it is, often seems to break down, for many animals, such as the Calanus, which normally make regular migrations, are found swarming right on the surface when the sunlight is particularly bright in the summer, and swarms of krill on the surface in the daytime are a common sight in the Antarctic. It is remarkable, too, that many of the tiny larvae which make up the temporary plankton show an exactly opposite habit to that of the permanent plankton. They move up to the surface by day and down to the deep layers at night. On most coasts there is an onshore wind by day which drives the surface water towards the shore and an offshore wind by night which drives the surface water in the opposite direction. Here, then, is a device by which the larvae of bottom-living animals maintain themselves in the shallow waters and tend to be driven in among the rocks and gullies where they will eventually settle.

The seasonal change of level seems to be a very different affair. If this is a response to light intensity, direct or indirect, it is one of a quite opposite kind to that which controls the daily movement, for as the summer

days begin to shorten and the light to fade the population sinks down towards the layers where there is even less light. It rises again to the surface when the light returns. Probably, then, temperature is now the most important influence at work.

As every animal of the plankton has its own most suitable temperature range, which governs and limits its horizontal extent, so it tends to seek those levels at which that temperature is to be found. Many animals which are found at the surface in temperate seas seek the deeper water in the tropics where they find their limiting temperatures. In the Antarctic the plankton inhabits the cold layer of water at the surface moving north and east during the summer but, with the onset of winter and the still further cooling of the surface water, the population seeks the warmer southward moving water below.

This winter movement downwards into deep water has been compared with the hibernation of animals on land and there are some marine animals which actually do hibernate. For instance, the polyp *Clytia johnstoni*, which around our coasts gives off its swimming bells profusely during the summer, dies down to a little rounded knob during the winter months but comes to life and proliferates its bells again in the spring. It is certain anyhow that the plankton animals which survive the perils and hazards of the summer and sink into the deeper layers in the autumn neither grow nor feed during the winter. At those depths, indeed, there are no diatoms for the plant grazers among them to feed on. The generation of the Calanus which sinks down in the winter carries an extra store of fat within the body on which it subsists during its sojourn in deep water.

Whatever the activating agency may be and whatever

the primary reason for it, this winter movement into deep water is extremely important. It brings about the constant renewal of the population in its natural waters. It ensures that each species, as it were, stays where it belongs. If all the animals in the Southern Ocean spent all their lives in the northward flowing surface water each would sooner or later be carried away out of the zone of water to which it is suited and the population would perish by being swept out of its natural environment. But the descent into southward moving water during the winter carries back and south again the population which will spawn next spring. In the North Atlantic the warm water of the Gulf Stream sinks from the surface and flows back towards the south at a deep level so that the plankton animals that are carried northwards at the surface in the summer tend to be carried back again during the winter. Some similar arrangement must hold for the diatoms also and perhaps the formation of resting spores in the winter, which sink by their own weight to deeper levels, may help to keep the ocean meadows in position.

It may be, too, that this winter sinking helps to determine whether a plankton animal shall live out in the open ocean as an oceanic species or close inshore as a neritic species. An animal which does not migrate up and down obviously cannot live in the open ocean since it could not maintain itself in position and would sooner or later be swept away out of its environment. Nor could an animal which needs to sink to lower levels in winter live close inshore where the depth of the water is insufficient. Close inshore along the coast of Norway, the Calanus dies out during the winter in many of the fjords where the depth is not great enough for the winter

descent and the fjords are repopulated again every summer from outside.

One of the most remarkable features of life in the sea is the similarity of the population, not only of the plankton but of the benthos and nekton also, in the temperate seas of the northern and southern hemisphere. There is no immediately obvious reason for this, since the two populations are separated by the broad tropics where the inhabitants are fewer and quite different. This general resemblance between northern and southern seas was noticed by the earliest explorers who saw that inhabitants of north polar and temperate seas were in many cases matched by southern counterparts. Nowadays we have an impressive list of animals and plants from southern waters which are not only similar to, but often identical with, those of the north. Even the whales of northern and southern waters are indistinguishable from one another, except perhaps in size, though, so far as is known, they never cross the equator. The chief difference between the inhabitants of the north and the south is the fact that many southern bottom-living animals have no free-swimming larval stage but grow straight into the adult from a young form very much like the full grown animal. Starfish dredged up from the bottom of the Ross Sea in the Antarctic often have minute but perfect young starfish adhering to them. This is perhaps a natural response to the rigours of life in cold seas, icebound for a large part of the summer when the free-swimming larvae would normally occur.

While the whole aspect of the population of northern and southern temperate seas is the same, so that it would need an expert, as a rule, to say whether any sample taken

with a net or a dredge came from the northern or southern hemisphere, yet the intervening tropical and warm water forms are quite distinctive. Some animals are continuous in their distribution through the tropics from north to south, as are the great red jelly-fish (*Periphylla* and *Atolla*) and the red prawns (*Acanthephyra*) which are found in temperate waters at the surface and in deep cold water in the tropics. They remain within their temperature range by sinking into the depths in warm waters. Nevertheless it is in the main true that there is a tropical discontinuity between similar northern and southern forms.

This phenomenon is known as 'bipolarity'. How it came about has long been a matter for discussion among naturalists. There is not only a bipolarity of the population but there is also a bipolarity of its behaviour, a matching of occurrences in the two hemispheres. The spring outburst of diatoms, the winter descent of the plankton, the large number of individuals but small number of species—all these are examples of happenings which occur both in northern and southern temperate waters but not in the tropics. They are the result of natural physical laws which ensure that the conditions of life shall be largely similar at the two opposite ends of the earth.

Now it is noticeable that there are many more neritic species than there are oceanic ones in all branches of marine life and, in the open ocean, many more species in northern temperate seas than in southern. It is a rule that any area with many species may be looked upon as having been populated longer than one with fewer and we may conclude that southern waters have been populated by dispersal from the north and that the open

ocean has been peopled from inshore. The habit of sinking in winter into south-moving deep water makes it clear how this might have come about, part at least of the northern population having been carried into southern waters in this way. On the other hand there is the possibility that since the conditions of life are very much the same in the open temperate seas of both hemispheres a certain amount of parallel evolution has gone on, producing similar forms in both the north and the south at the same time. It is also possible that the northern and southern populations are the remains of one which was once universal all over the globe but that the tropical part of this world-wide fauna has now disappeared and been replaced by a more recent and more diverse one. Probably all three of these explanations are in some degree true. Quite recently it has been shown that a northern species can be transferred to the south and will flourish there if the right conditions prevail, for the North Pacific salmon has been artificially transferred from the Canadian rivers to those of the South Island of New Zealand—a particularly delicate adjustment since conditions must be exactly right in both the freshwater rivers and in the sea.

The life histories and development of the more important members of the animal plankton have been fairly closely studied, but on the whole the biology of plankton animals is not very well known.

The copepods are always the most convenient examples of the general life history of plankton animals, since they are perhaps the most important members of the zooplankton.

Like many other plankton animals the copepods start life as larvae. The copepod larva is a microscopic

oval creature, called the nauplius, with comparatively enormous forked oar-like legs and antennae. The copepods grow by jumps and stages, as all Crustacea do, casting their skins and growing new ones between the stages. Each stage represents an advance in development, in complication of structure and progress towards the adult condition. There are six oval nauplius stages, after which the larva becomes a young copepod, recognizable as such in appearance. There are five of these copepodite stages, as they are called, each larger and more perfect than the one before it, until the sixth stage, which is the adult, is reached. In the Norwegian fjords there are two kinds of Calanus (*C. finmarchicus* and *C. hyperboreus*), both important as the food of herring. These produce their swarms of oval larvae in the fjords and in the open sea outside, where they are found in gigantic numbers in the surface in the spring. One of these copepods (*C. finmarchicus*)—the 'brit' of the Channel and North Sea—lives and spawns close inshore in the fjords. It produces three separate and distinct broods of larvae during the summer. Each brood grows up rapidly in the space of a month or two and, as the stages of each brood advance in size and weight and perfection of structure towards the adult, they tend to concentrate in deeper layers of water. The last brood, which hatches out late in the summer, does not change into the adult stage in that year but the late stages, not yet full grown, sink into the water at the bottom of the deepest fjords, to a depth of some 600 to 1,000 feet, and there they pass the winter as adolescents, or near-adults, in the last stage before the adult condition. In the spring these change into the adult stage and migrate to the surface again, where they shed their eggs. The other

Calanus (*C. hyperboreus*) is an inhabitant of the deeper water offshore. It brings forth only one brood of young in the summer which grows much more slowly than any of the three spawned by its inshore cousin. The young of the spring generation tend to concentrate in lower and lower layers the older they grow and in the autumn sink into the deep water without becoming fully adult. They go even deeper than the wintering brood of the inshore Calanus so that they mostly pass the winter in the deep water off the coast since most of the fjords are too shallow for them.

The life history of the krill, so vital to the whale fishery as the food of the great whales of the Antarctic, has been studied closely for some years by the scientists of the *Discovery* Committee and by the Norwegians. Their work is not yet complete but it is known that the krill, unlike most other animals of the plankton, takes two years to become fully grown. Indeed its life history seems to be the exact opposite of that of the copepods for, while the full-grown animals swarm in the surface layers in the summer, they apparently sink down into the deep water to shed their eggs, because the ripe females carrying eggs, the eggs themselves and the very earliest young stages, were taken only in the deepest water by the *Discovery II* close to the Antarctic continental shelf. The egg hatches as a small oval larva, a nauplius not unlike that of the copepods but much larger, and this goes through a most complicated series of stages leading up to the adult. The krill goes through about a dozen of these stages but some of the Euphausiidae, the order to which the krill belongs, go through as many as thirty-two stages, not including the adult, each becoming progressively more complicated. The young

krill rise to the surface gradually during the course of the summer but sink again with the rest of the plankton in the autumn and, during the winter months in the deep water, growth is slowed down. The krill spawns in the second summer after hatching, but some of its northern cousins spawn twice, once in the first and again in the second summer after hatching.

CHAPTER V

THE SEASHORE

Conditions of life in the tidal zone—Wave action—Exposure—Fluctuations of temperature and salinity—Zoning of life on the shore—Zoning of seaweeds—Zoning of animals—The rocky shore—The sandy and muddy shore—Spawning habits of shore animals—Care of the young and egg—Animal associations—Commensalism—Symbiosis—Parasitism.

No region is more exciting for the naturalist, or more enchanting for the lover of beauty and colour, than the narrow fringe of shore and shallow water where sea and dry land meet—a world as strange and various as the tropical jungle. It is probably the cradle of life from which both the hydrosphere and the lithosphere were populated, a world of great antiquity, for the study of fossil invertebrate animals leads us to suppose that the seashore of Cambrian times was not very different in aspect from that of to-day. In this realm of complex and continually changing conditions an enormous variety of creatures has evolved with a multitude of different devices for obtaining those necessities of life, oxygen, carbon dioxide, light and food. Competition for these things is intense and plant and animals have learnt to live together in associations for mutual benefit and to prey upon each other as parasites. They have adopted methods of attack and defence and tricks of protection and concealment which are baffling in their variety and complexity.

We must be content here to describe briefly the kind

of conditions that prevail on the shores of temperate coasts and to give a necessarily sketchy picture of the plant and animal associations that one might expect to find on the lovely rocky, sandy or muddy beaches of our own British Isles, so dear and so delightful to their people of all ages. To attempt to picture also the shore life of the tropics would be too great a task.

Life on the shore presents plants and animals with problems of a very special kind. They arise chiefly from the fluctuating nature of this narrow strip where the conditions of two worlds meet and intermingle. Land and sea merge gradually into one another from the strip along the high tide mark, where conditions are mainly terrestrial, to the shallow seas below the low tide mark where conditions are mainly marine. Between the tide marks is the tidal zone—covered and uncovered twice every twenty-four hours by the advancing and receding tide. It is a zone where living things must be able to withstand extreme variations in all the factors governing their lives, with terrestrial influences increasing towards the high tide mark and marine towards the low. Between the level of the low water neaps and the low water springs is the strip where life is most abundant, where bright light and oxygen are most accessible and where the danger of drying up or of excessive heat or acidity are least. Here, too, competition and the struggle for existence are keenest. The battle for living space and food has equipped the animals of this zone with biological and mechanical weapons of great efficiency. Below the level of low water springs is the continental shelf zone above the hundred fathom line where maritime conditions increasingly predominate and the terrestrial influences of fluctuating temperature and

salinity, increased acidity, bright light and the mechanical action of waves and tides gradually diminish towards the continental edge where the shelf steepens into the slope and the sea floor descends into the abyssal zone.

The tidal zone, the strip of half-land and half-sea between the tide marks, is predominantly the region of the benthos. Although conditions on the shore are so favourable for life in the abundance of food and light and in the well aerated water richly supplied with salts, nevertheless the shore presents several great disadvantages. Two of these are purely mechanical. The whole population is four times daily exposed to the battering action of the waves as the tide advances and recedes and to the dislodging effect of local currents, swirls and eddies which tend to carry living things away from their natural homes. The great majority of the population, therefore, has anchored itself to the firm rocks or stones or has taken to burrowing into the soft sand and mud. Animals which can swim or move actively can escape, when conditions become unfavourable, into deeper water, but those which have chosen to remain more or less fixed must be capable of withstanding this pounding by the waves. They must also be able to deal with the second mechanical disadvantage of their surroundings—the twice daily risk of being dried up when the ebb leaves high and dry the rocks and stones to which they cling, or the soft sand or mud in which they burrow.

The pounding of the waves has impressed upon all the inhabitants of the shore a general flattened shape. We find this most emphatically on a rocky shore among animals which cling to rocks and stones or live in crevices. It holds good rather less on sandy or muddy shores where animals can burrow down into the soft

hospitable oozy bed away from the turmoil above. Yet many of the burrowers too have a flattened shape. The prevalent outline of shore animals, then, may be looked upon as that of a fish cut in half down its middle line with the lower cut surface pressed against the substratum to which the animal adheres and the upper surface more or less streamlined to meet the flow of water. The majority of animals that live exposed to the action of the waves are moreover flattened from above downwards like the limpet or the sea-slug (*Doris*), like the crabs and the starfish, but some Crustacea are flattened laterally like the sand-hopper that lives in piles of decaying seaweed along the high tide mark. Further, the same kind of animal may have a different shape according to whether it lives in a sheltered or exposed position. Limpets which live in sheltered rock pools are high and rounded while those which live within the dash of waves on the seaward faces of the rocks are flattened and more oval in shape. In these exposed positions we find a great many animals growing encrusted upon the rocks, encrusting sponges, the many squirts and sea-mats. All these live mainly around the low tide mark where there is the least possible risk of drying up. Close pressed against the rocks they present smooth unresisting surfaces to the action of the waves.

Another and obvious way of avoiding the action of waves is to seek the shelter of crevices and overhanging positions or the landward faces of sloping rocks. Anyone who knows the seashore will have noticed how the sheltered nooks and crannies are a mass of living things of endless beauty and variety, the sea-anemones, the urchins and starfish, the sponges, the sea-mats and the polyps so that the mysterious dark cool hiding places

seem to drip with life, secret and intent on the hard employment of simply being alive. The external skeletons of Crustacea, the coiled tubes of the lovely tentacled worms and the shells of molluscs may also be classed among the devices which protect their owners from the turbulent world they live in.

Animals cling to the rocks in many ways. Most of the molluscs, such as the limpet, have a large muscular expansion on the undersurface of the body called the foot. It was at one time thought that the limpet clung to its home by suction but it seems more probable that it does so simply by following with the soft under face of its foot every minute roughness of the rock. The edge of the shell also seems to have a rasping action for a fine ring-shaped groove is left upon the rock, worn by the edge of the shell, when a limpet is removed from its site. The anemone, too, clings to the rock simply by filling every rugosity of the rock face with its flesh. All encrusting animals also are so intimately related to their substratum that they cannot be removed except by the most violent means. The common barnacle, however, cements itself to the rock with a secretion which glues down the basal plate of the little box in which it lives and the mussel attaches itself by a bundle of coarse fibres called the byssus.

Burrowing and tube-living animals can mostly escape the more violent action of the waves by simply sinking deeper into the sand or mud or by withdrawing into their tubes and closing the door as many of the worms do. Some of these have gill filaments modified to form a plug which, when drawn back into the tube, stops up the entrance. Many of the molluscs, such as the dog-whelk, carry a lid, called the operculum, on the upper

surface of the tail which, when the animal is withdrawn into its spiral tower, closes the opening like a door. But many of these burrowing creatures do not burrow very deeply and must remain only lightly buried in order to breathe. They too have the flattened shape in common with their fixed and stationary cousins, as we see in the heart-urchin (*Echinocardium*), the cockle (*Cardium*) and the many burrowing crabs (*Corystes* and *Portunus*).

Many stationary animals have some power of movement. The starfish and the urchin are almost agile on their myriads of tube-feet like fountain-pen fillers. The limpet can arise, take up its house and walk when necessity compels. The mussel can move with difficulty from one place to another by hauling itself up on its bundle of fibres, snapping the old fibres and growing new ones. But these creatures can, as a rule, only move short distances and slowly. Encrusting animals, of course, cannot move at all. The vast majority of the inhabitants of the shore, therefore, are exposed twice daily to the risk of being dried up when the tide recedes. It follows that they must either be able to withstand a certain amount of drying up or develop some means of retaining enough moisture until the returning waters cover them again. Further, since most of them breathe oxygen dissolved in water and cannot breathe air, they must either retain enough moisture for normal respiration to continue during their hours of exposure or be able to remain for some time in a state of suspended activity. For the molluscs, for the tube-living worms and for the burrowers generally all this is easy enough. They withdraw into their houses and shut the door. Burrowers shrink deeper into their holes. But the common barnacle

is often found covering the rocks in places where it remains exposed and dry for days at a time and it has been calculated that, in some of the less favourable situations it may light upon, the barnacle may spend only one-twentieth of its life under water. The barnacle is a small shrimp-like creature which, when the tide covers it, stands upside down in its box made of plates of lime, feathering food towards itself with its long curved legs. When the tide recedes it closes its box by means of four accurately fitting valves. In doing so it entraps a bubble of air and enough moisture to keep its gills damp. If you listen carefully just after the tide has left the rocks you may hear all around the whispering talk of the barnacles, a faint crepitation. It is caused by the tighter closing of the valves in millions of little houses whose inmates are alarmed by the monstrous reverberation of your bare feet. The clicking sound is the rupture of the air bubble in each one. Thus, tightly battened down like a ship in action, the barnacles remain inactive, not feeding at all nor breathing very much for weeks at a time. Around our shores there are four species of periwinkle (*Littorina*), little snail-like shells that cling to the rock faces in great numbers. The amount of exposure to air which each of these periwinkles is able to withstand is different for each one so that they occur in graded zones or bands along the shore from above the high tide mark to the low. One of them (*Littorina neritoides*) lives above the high tide mark in crevices and the mere moisture of the air in such a situation is enough for its needs. It can withstand exposure to completely dry air for as much as forty-two days. Another (*L. rudis*) lives just below the high tide mark and can withstand an exposure of thirty-one days to dry air. Strangely

enough another periwinkle (*L. littorea*), which lives nearest the low tide mark, can withstand twenty-three days' exposure, while the one (*L. obtusata*) which occupies the half tide zone can only withstand six days. The latter periwinkle, however, needs the thick growths of the bladder wrack seaweeds for protection against drying up and is seldom found unless this weed is present. For this reason this periwinkle is a good deal less used to exposure than its cousin farther down the beach.

By preserving moist conditions and protecting a host of small creatures from drying up, the rich growths of seaweed play a part of immense importance in shore life. You have only to turn over the apparently dry cushions of the bladder wrack to find a damp flourishing world beneath full of small molluscs and Crustacea. The protecting fronds cover the delicate egg bands of molluscs and, even when dead, stiff and rotten, are the home of sand-hoppers and mites, which gain moisture and warmth from the dead piles of weed lining the high tide mark. In addition the fronds of all the seaweeds form a substratum for a great many encrusting creatures such as squirts, polyps, sea-mats and tube-living worms. The white limy spots that everyone will have noticed on the blades are the coiled tubes of a little tentacled worm (*Spirorbis*). The bases of the fronds of all the larger weeds are furred with branching polyps and the branches anchor of the ribbon weed, which grows below low water, are the home of a great variety of small animals.

It is not only to find protection against the violence of the waves, but also to avoid the risk of drying up that life tends to collect in crevices and cracks in the rocks, on sheltered and overhanging faces and in damp quiet corners. Here many animals can remain for quite a

long time not actually submerged if the air is damp enough to keep their tissues moist.

Another of the hazards of life on the seashore is that which arises from the rapid and extreme changes of temperature to which many regions of the tidal zone are exposed. These are both seasonal and daily changes and, as one might expect, are more extreme in the temperate regions, where there is a great difference between summer and winter and between night and day, than in the tropics where day and night and summer and winter merge into a constant and perpetual warmth. In temperate regions rocks and stretches of sand become heated up during the day, when the tide is low, and cooled again at night. On gently sloping beaches the water, running over heated rocks and sand, is warmed by contact. Rock pools, far above the low tide mark, as everyone knows, become very much heated by the sun. The effect of the warming of the water is to drive off the oxygen which is less soluble in water at higher than at lower temperatures. Animals therefore die of suffocation. Some, such as sponges and anemones, however, can become quiescent if the temperature is too high and many Protozoa form a resting stage if the temperature becomes unsuitable for them in either direction. On the shore, just as in the open ocean, every animal has a range of temperature which is most suitable for it. In the temperate regions, because on the whole temperatures vary more, most animals have a much wider temperature range, that is—they can tolerate more extreme changes, than animals that live on tropical shores. On the whole tropical animals live within about 5° C. (9° F.) of their most favourable temperature and within 10°–15° C. (18–27° F.) of their upper fatal limit.

But on many temperate coasts the population may have to put up with temperature ranges varying from freezing in the winter to 27° C. (80° F.) and more in the summer.

The salinity of the water also changes continually on the shore and in the shallow water zone. The reasons for this are obvious. In estuaries there are all stages of salinity from that of the open ocean to that of the fresh water of the river and all along the shore there is scarcely a bay or inlet that does not receive some fresh water drainage from the land, either from streams running into the sea or from drippings and seepings from the cliffs. In rock pools exposed to the sun evaporation may increase the salinity to as much as 300 parts per thousand. Rain water, of course, has the opposite effect. The shallower and more exposed the pool, naturally, the greater the variations of salinity, temperature and other conditions to which the inhabitants are exposed.

As for temperature so for salinity every animal has a range which is most suitable for it, and animals and plants which live on the shore, or in the shallow water zone, have a far greater range and a far greater tolerance than those which live in the open ocean. Mussels, barnacles, oysters and limpets can live in estuaries where the water is almost fresh. Nevertheless only those mussels and oysters whose beds are situated within a certain range of salinity ever grow to marketable size. They become stunted and deformed if the water is too fresh. The green slime weed of the rock pools near the high tide mark (*Enteromorpha intestinalis*) and the green sea-lettuce (*Ulva latissima*) can tolerate conditions which vary from almost fresh water, when the pools are diluted by rain, to immense concentrations when the pools are evaporated by the hot sun. Among these weeds live

enormous numbers of a minute copepod (*Harpacticus*) which can also withstand these rigorous conditions and seems to do so by retreating into the filaments of the Enteromorpha when the water becomes too concentrated. But the sensitiveness of animals to changes of salinity is plainly shown by the ship-worm (*Teredo*). This is a pest which sometimes invades harbours in great numbers, boring into and honeycombing wooden structures and the unprotected bottoms of ships. But it has been found that if there is a heavy fall of rain, which dilutes the water in the harbour, the pest decreases, resuming its ravages again when the next dry spell comes along and the salinity of the water increases again.

There are also other conditions, vital for the well-being of plants and animals, which vary a great deal more on the shore and in the shallow water zone than in the open ocean. The density of the water in rock pools varies with the temperature and the salinity, increasing as the salinity rises or the temperature falls. On the whole the salinity has the greater effect of the two since it is subject to more extreme variations. When the salinity and the temperature both increase, the oxygen content of the water falls and many animals which inhabit pools are able to die down to a quiescent state when this happens. Altogether the animals and plants which live in this varying and diversified region need to be extremely hardy. The hardiness of many of them has been proved in the laboratory by exposing them to artificial extremes and it has been found that a great proportion of the population is tough enough to withstand for long periods conditions that would soon kill off their more delicate relatives of the open sea.

The finely graded conditions from the high tide mark

down to the shallow sea below the low water springs has brought about a zoning of life on the seashore. Owing to the bright light and the abundance of dissolved carbon dioxide and oxygen in the water, every suitable situation along the seashore supports profuse growths of plant life, the seaweeds. The vegetation is much more local in its growth than it is on land and its arrangement in zones parallel with the tide marks is perhaps the most striking thing one notices in walking from the high to the low tide level. The animals are zoned also, though less obviously, partly in association with the different zones of weed and partly according to the quality of the beach and to the variety of environment which it presents for animal life.

The number of different kinds of plants which grow on the shore is comparatively small. They all belong to the family of the Algae—the blue-green algae, the green, the brown and the red. They have no anatomically differentiated stem and leaf as have the flowering plants and there is no definite vascular tissue. They reproduce in a great variety of ways and exhibit many differences in the form of the thallus as the leaf-like expansion is called. The roots are merely holdfasts, having no absorptive function, gripping tightly the rocks on which the weeds grow and often harbouring a large assemblage of animal life in their protecting interstices.

At a glance we can see that there is a zoning of the seaweeds according to colour, for the blue green and green weeds live along the high tide mark and the brown weeds between the tide marks. Red weeds grow near the low tide mark and in small clear pools among the rocks at higher levels.

Along the high tide mark itself, along cliff or rock faces

and in rock pools we find the slippery green slime (*Enteromorpha intestinalis*) which waves fine, hairy filaments when covered by the tide but makes a thick, soft, slimy mat when the tide is out and is dangerous to walk upon. In the summer, if it has been left exposed for some time, it dries to a hard white line. Here too are the thin green films of the sea-lettuce (*Ulva lactuca* and *U. latissima*). It grows in pools near the high tide mark and, if the pools evaporate in the hot sun, it becomes rank and coarse and of a dark green colour. Between the tide marks are profuse growths of the seaweeds which we call the wracks, covering with their dense cushioned groves every available rock and boulder. They too are arranged in zones. Just below the high tide mark is a zone a few inches to a few feet wide, according to the slope of the beach, which is occupied by the channelled wrack (*Pelvetia canaliculata*), olive green with thin grooved fronds ending in little heart-shaped reproductive organs. From this zone to low water brown wracks predominate and this is usually called the fucoid zone because the weeds mainly belong to the genus *Fucus*. Below the channelled wrack there is a belt of the flat wrack (*Fucus platycarpus*) with broad smooth fronds without bladders and then a belt of the knotted wrack (*Ascophyllum nodosum*). This is easily distinguished by its very long slender fronds with single bladders along the middle. This weed is of especial importance in absorbing wave shock since its long narrow fronds, often six or eight feet in length, float out upon the surface of the water and break the violence of the waves. It requires a moderate amount of shelter for its best development and almost always bears small tufts of a stunted red weed (*Polysiphonia fastigatum*) growing upon it. These

two wracks, the smooth and the knotted, occupy a zone which varies in width from 20 feet to 30 yards according to the slope of the beach. They are succeeded by a zone of the bladder wrack (*Fucus vesiculosus*) some 10 feet to 50 yards in extent. This is the familiar weed with air bladders arranged in pairs or threes which it is fun to pop when dry. Occasionally the belt of *Fucus vesiculosus* occurs higher on the shore than *Ascophyllum.* Next, nearest to the low tide mark, comes the zone of the notched wrack (*Fucus serratus*) with toothed edges to the fronds but no bladders. This also occupies a zone from 10 feet to 50 yards wide and is perhaps the most strongly growing of all the wracks, dense hospitable groves giving moisture and shelter to a host of creatures at low tide. Below the low tide mark the wracks end quite suddenly and give place to the zone of the ribbon weeds (*Laminaria*). These are never exposed except at low water springs and they extend down to a depth of about twenty-five fathoms where the growth of seaweeds ends. The ribbon weeds, whose broad flat bands we hang up to tell the weather, are the largest of all the seaweeds, but simple and undifferentiated like all the rest in spite of their great size. The largest of all is the kelp which grows in such profusion in southern waters. It reaches up to the surface from depths of thirty or forty feet with broad crenellated bands ten or twelve feet long buoyed up by air bladders.

These zones of weed are not always present on every shore for one or more of them may be missing and the presence of each is dependent on the amount of shelter the shore provides. One of the wracks (*Fucus platycarpus*) does not like sheltered positions but the bladder wrack cannot stand much exposure. There are also other weeds

which may be found among them such as the carrag-heen or Irish moss (*Chondrus crispus* and *Gigartina stellata*), with forked reddish-brown fronds, which grows near the low tide mark and is collected and eaten on the coast of Ireland and in the Hebrides. Another red weed, the dulse (*Rhodomenia palmata*), with flat fronds, is eaten on the coast of Scotland and the laver (*Porphyra laciniata*), a thin filmy weed, red but otherwise rather like a sea-lettuce, is collected and eaten in Wales. In addition to these we find, in exposed rock pools, the encrusting corallines, stiff and pink in their skeletons of lime. In the pools they are small brittle encrustations but below the low tide mark grows the larger *Lithothamnion* forming rounded cushions in situations where the water is rough, but branching tufts lower down where conditions are quiet. These, in spite of their appearance and limy consistency, which leads to their being spoken of as coral banks around our coasts, are nevertheless seaweeds. In the tropics the Lithothamnion and other coralline weeds do take part in the formation of coral reefs forming encrustations over the true corals and binding the reefs together.

The fauna of the seashore is too various and diverse to describe in detail. Its colour and beauty have excited the imagination and wonder of mankind since the time of Aristotle. Like the plants the animals tend to show a certain amount of zoning but the grouping, as one might expect, varies according to the nature of the beach, that is—according to whether the substratum on which the animals live is a rocky one or made of sand or of mud. Each kind of substratum supports its characteristic association of animals and on these associations a linear arrangement is to some extent imposed by the amount of

moisture or exposure to which the animals are suited. Along the high tide mark, for instance, there is a zone of animals which live under almost terrestrial conditions and need no more than the moisture of the sea air for breathing. Creeping about at dusk in this region, under flat stones and in crevices, we find the great rock louse (*Ligia*), like a very large woodlouse an inch or so in length. This, it would seem, is a marine animal which is in process of migrating from the sea to the land and has almost become terrestrial in habit. At this level too, in piles of rotting seaweed on a sandy beach, are the sand-hoppers (*Orchestia* and *Talitrus*) which jump in all directions when disturbed, flicking themselves forward by a sudden straightening of their flexible backs. Several kinds of insects live here also, such as the little spring-tails which catapult themselves by means of a special lever fashioned out of their tails, and a number of small beetles. But the most beautiful linear zoning of all the animals on the shore is shown by the little periwinkles which have already been referred to. One of these (*Littorina neritoides*) lives high on the rock faces, often in positions where it is only covered at high water springs. Another (*L. rudis*) lives just below the high water mark. Another (*L. obtusata*) lives between the tide marks always on the fronds of one of the wrack weeds, while the larger common winkle (*L. littorea*) lives along the low tide mark.

On the whole, if we climb about a rocky shore, we find that the animals can be arranged in groups according to whether they live on rocks, stones or weeds, or under stones, or in crevices among the rocks. Each of these situations has its own association of animals which, within the limits of their own environment, are arranged

in zones, sometimes quite definite and sometimes diffuse. For instance, we find the common barnacle, while scattered everywhere about the shore, flourishing best in a zone along the high water mark. The dog-whelk (*Purpurea*), too, lives in the upper half of the shore, feeding on barnacles and mussels. Lower down are the beautiful banded conical top shells (*Gibbula* and *Calliostoma*). Around the low water mark the mussels flourish best and here too we find small scallops which jump through the water by clapping their shells together. Here too are dense growths of encrusting animals often covering the rock faces with a soft thick carpet of living things, rounding the jagged outlines with a soft pelt. Here live the bottle squirts, bulbous masses which spurt a steam of water outwards at a touch, and the golden stars squirts (*Botryllus*) which cover the rocks with a layer of firm jelly studded with little yellow stars, each a radial colony of individuals. Sea-mats cover the rocks and the fronds of weeds with their gauzy films and everywhere there is a fur of polyps waving microscopic fingers. In overhanging and sheltered nooks hang down the little purse sponges (*Grantia compressa*), like small soft bags, and the bread-crumb sponge (*Halichondria panicea*) spreads everywhere its soft masses. Here, too, are the gooseberry squirts and the coloured anemones—such a wealth of life in fact that every available inch of rock is covered with living, growing creatures, waging a furious silent war with one another for their share of those elements of life—food, light, oxygen and living space. Indeed we may say that one of the things we notice most about the rocky shore is the abundance of life at the level of high and low tide and its comparative scantiness in between. This is because conditions are more stable at these two extremes,

more uniformly terrestrial at high water, more uniformly marine at low water. Here too the pounding action of the waves is felt only twice daily—at high and low tide—while in between it is felt four times—twice on the flow and twice on the ebb. Certain animals, of course, live everywhere between the tide marks, like the limpet which browses on seaweeds, or the little worms (*Spirorbis*) which pock mark all the fronds of the seaweeds with their hard little coiled limy tubes. But the majority of the population seeks the high or low water level where the waves pound upon the rocks for the shortest time, the hardier animals that can withstand exposure along the high tide mark and the more delicate and sensitive along the low tide mark.

Under stones between the tide marks live a great many worms, both naked and tube-living. The long bootlace worm (*Lineus*) is often found under stones, sometimes tied into an almost inextricable knot. If it is carefully unravelled in a basin of water—a difficult feat to perform without breaking the delicate body—it may be stretched out to a length of several yards. Many bristle worms may be found by turning over stones. A common one is the yellow *Cirratulus cirratus* which lives in sandy mud beneath flat stones with only its tentacles showing. It keeps as much of its body as possible in contact with the stone and, if placed in a dish of water, will wander unhappily about the dish, but if a stone is placed in the dish, immediately hides beneath it. The handsome iridescent rag worm, *Nereis cultrifera*, with its bulbous pharynx, which it extrudes from its mouth like a balloon, and its rows of bristles projecting laterally along the body, is found in great numbers under stones near low tide and is often used as a bait for fishing. Besides the

many worms there are a great number of crabs that scuttle away from almost any stone we like to turn over, such as the fiddler crab (*Portunus puber*) and the hermit crabs. These have a soft tail unprotected by a shell and live in the empty uninhabited houses of molluscs, whelks or top-shells, clinging on to the central column of the spire by means of special claws at the hinder end of the body. When in due time the hermit crab grows too big for its house it forsakes it and scuttles to a new one, but no force or persuasion can make it leave its house unless it wishes to. On the silver sands of some coral islands every square inch of ground is covered with tiny hermit crabs, inhabiting millions of little shells, so that the sand seems to be alive with them as you walk. Under stones, also near low tide, we find many starfish and sea-urchins, including the little cushion star (*Asterina gibbosa*) with its arms joined so as almost to form a pentagon.

In nooks and crevices we find many of the animals just mentioned as well as the encrusting ones. There may also be bivalve molluscs (*Saxicava* and the larger piddock—*Pholas dactylus*) which live in tunnels which they bore into the rocks. The empty burrows are often inhabited by a small green worm (*Eulalia viridis*). Here, too, tightly wedged in crevices, are the little soft sea-cucumbers (*Cucumaria*). In pools among the rocks, those haunts of mystery and still beauty, nearly all these creatures may be found. Every one knows the sea-anemones too, open like flowers and awaiting a chance prey or shut apparently in sleep. In the deeper pools we find the beautiful naked sea-slugs (*Doris*) with filamentous gills upon their backs. They are molluscs without shells. The odd-looking velvety sea-hare (*Aplysia*), with its ear-like tentacles from which it gets its name, is

a mollusc whose shell is enclosed in folds of flesh. It is found gliding about in deep pools in the summer months when it comes inshore to spawn from deeper water.

A sandy or muddy shore has quite a different population from a rocky shore. Most of the animals are burrowers as one might expect, for there is no solid foundation for fixed or encrusting animals. A great number of burrowing molluscs live at various depths, some quite near the surface like the cockle, but others much deeper like the razor shell, which lives at a depth of a foot or so. There are also a great many burrowing and tube-living worms. Most of the shallow burrowing animals are those which live in coarse sand which is continually being shifted by tidal streams and currents. They run the alternate risks of being laid bare by the sand and rolled away by the streams one moment and of being smothered by shifting masses of sand the next. For this reason most of them are fairly agile burrowers. They can cover and uncover themselves quickly like the starfish, which can sink vertically into the sand in an astonishingly short time, or the shore crab which buries itself very quickly by shovelling sand on to its back. Many of them have ridges or spines or projections which help to anchor them in the sand, like the blunt teeth on the shell of the spiny cockle (*Cardium aculeatum*) or the long backwardly directed spines of the heart urchin (*Echinocardium*). A stout globular shell, like that of the cockle or the clam, helps to withstand the lateral pressure of shifting sand. Most burrowing animals, however, live fairly deeply buried and do not move much once they have settled in their oozy lair. They do not run the risk of being laid bare but they do have to withstand a

certain amount of lateral pressure. They also have to find some method of breathing while firmly buried six inches or a foot below the surface. The molluscs which live not very deeply buried have rather stout shells, like the clam or gaper, but the deeper ones such as the razor shell (*Solen*) have quite thin ones because at the depth at which they live there is little lateral pressure. They solve the breathing problem by developing a stout leathery tube formed by an extension of the fleshy skirt which lines the shell. In the clam or gaper (*Mya truncata*) which lies buried in soft mud, and in the razor shell, this leathery tube unites two passages for water—one an entrance and the other an exit—but in the hen shell (*Mya gallina*) the two tubes are quite separate. Thus the burrowing molluscs can lie beneath the surface of the mud or sand with a breathing tube, like the schnorkel used by German submarines during the war, opening to the water above. The razor shell is an active burrower and is very difficult to find even by digging for it. The valves of the shell form a cylinder with the breathing tube at one end and the muscular foot projecting at the other. The end of the foot can be expanded to form a sort of anchor upon which the animal drags itself down rapidly into the sand if disturbed.

The burrowing and tube-living worms are among the most beautiful animals of the shore but they are seldom seen in their true beauty, except in tanks, because, when the tide is out and the sand uncovered, they retreat into their homes and nothing can be seen of them. The most familiar of the burrowing worms is the lugworm (*Arenicola marina*), so often used as a bait for fishing. Its habit is like that of the earthworm. It lives in fine mud or sand, but deeper than most of the molluscs, and makes

U-shaped burrows, passing the sand in at one end and out at the other, just as the earthworm does, by rhythmic contractions of its body. It extracts decaying organic material for its food from the sand which it passes through the intestine and, when the tide is out, the used sand piles up as the familiar cast at the tail end of the burrow. The head of the worm, with its delicate bushy gill filaments, lies at the bottom of the U. The terebellid worms build tubes of sand or mud or bits of shell bound together with mucus and live inside them with their long feathery tentacles protruding when the mud is covered, but withdrawn when the tide is out. The serpulid worms protrude from their tubes a beautiful fan-shaped crown of tentacles which makes them look more like flowers than worms. All these need very calm estuaries and backwaters where the fine mud can settle gently and, at the least touch, they fold up their fans and slip back into their tubes. Where rocks run out into the sand the reef-building worms (Sabellidae) build their honeycombs of hardened sand in each cell of which lives a worm, exposing its crown of delicate tentacles when the reef is covered.

The bitter struggle which is life on the seashore has led the inhabitants to adopt a great variety of spawning habits. A large number of them, barnacles, sea-urchins and mussels, simply shed their eggs and sperm into the water at the same time and the egg, thus haphazardly fertilized, grows up into a larva which is quite unlike the grown animal and which, after a youth spent as a member of the temporary plankton, settles down in middle or late summer, if it can find a suitable foothold, and assumes the adult shape. This method of reproduction involves many and serious risks, for even if the egg

succeeds in becoming fertilized it, or the larva it becomes, may be swept out to sea, or eaten by one of its innumerable enemies or, finally, may fail to find a suitable place to settle on. The fecundity of all animals that use this method of reproduction is therefore enormous, along the shore just as in the open ocean. The American oyster produces 115,000,000 eggs at each yearly spawning and one of the sea-hares (*Tethys*) 500,000,000. But from this free and careless method of spawning, in which both egg and young are abandoned to their fate in the water, there are gradations of parental care for the egg and for the young up to the production of complete and perfect young from inside the mother's body, such as we see in some of the rock fish (the blenny, *Zoarces viviparus*). Nothing, in fact, could illustrate better the transitional character of the seashore than the wide range of methods of caring for the young which is often found in closely related animals. For instance, we find that the periwinkle (*Littorina littorea*), which lives along the low water mark, deposits its eggs in little unattached capsules, each shaped like a tin helmet and containing one egg. The free floating larva hatches out in quite an early stage. But the periwinkle which lives higher up the shore (*L. obtusata*) lays its eggs in a film of jelly on the fronds of the wrack weed. Because of the greater risks to a delicate free larva between the tide marks the eggs do not hatch out until the embryo has reached a considerably more advanced stage. The periwinkle that lives above the high tide mark (*L. neritoides*), on the other hand, produces small but perfect young from the body of the mother. Thus the mode of life and nature of the animal's surroundings impress themselves on its life history. Again, the shore crabs, which leave the shore to spawn

in rather deeper water below the low tide mark in late summer, have a normal life cycle which involves six larval stages. The early stage is known as the zoaea (Fig. 7*b*)—a tiny hooded creature with a spine on its back which serves the double purpose of increasing the surface area and of discouraging enemies who might be tempted to swallow it. This is followed by a number of further stages during which the larva becomes more advanced in structure and then comes a stage known as the megalopa—which means 'big eyes'. It has a pair of relatively enormous eyes and a definitely crab-like appearance except that the hinder part of the body is not curved underneath the fore part. The megalopa changes into the adult form. But in the shrimps and prawns, which do not seek the safety of the deeper water during spawning, the zoaea stages are skipped and the larva hatches in a very late stage resembling the grown form. Sometimes, again, the actual spawning time of an animal may undergo adjustment and alteration if conditions are unfavourable for spawning at the normal time. In the Mediterranean, for instance, some of the harbours and creeks become stagnant and putrid in the heat of summer. They are inhabited by animals which mostly reproduce in the winter and early spring.

Shore animals have adopted many different methods of protecting and caring for the egg itself. Many of the rock-fish guard their eggs, like the gunnel (*Centronotus gunnellus*) which lies curled around its masses of eggs under stones until they hatch, or like the lumpsucker (*Cyclopterus*) in which the male fish stands guard over the eggs. Most of the shore-living crustacea, too, carry their eggs about with them and crabs or lobsters in berry are a common enough sight in the summer. The masses of

eggs are attached to the legs beneath the hinder tail part of the body by means of a sticky substance. As a general rule, however, shore animals do not themselves protect their eggs. If they do not simply shed them into the water they deposit them somewhere, on rocks or on weed, either attached to the substratum or else protected by some sort of capsule or casing. Any wanderer about the foreshore has seen along the high tide mark the dead egg capsules of the common whelk or buckie (*Buccinum undatum*). They resemble large rattling masses of sago pudding. The egg masses of the dog whelk (*Purpurea*) are common enough too. You may find masses of them in sheltered crannies among the rocks, each capsule like a pinkish grain of wheat attached by a short stalk at one end. And in pools there are the coiled gelatinous ribbons, containing hundreds of thousands of eggs, laid by the sea-slug.

In their battle for existence and for living space the inhabitants of the shore enter into every kind of association with one another. These range in their effect from the kind of association in which animals merely live together as neighbours, sharing the same laminaria root or the same chink among the rocks, up to true parasitism such as we see in the crabs infested by the weird sac-like barnacle parasite *Sacculina* (Fig. 8). In between these extremes there are many degrees of intimacy of association and more than one are often found together within a single group or association of several animals. A mussel bed forms a good and simple example. The mussels grow on top of one another so thickly that eventually the lower ones are suffocated by those above. Little green pea crabs (*Pinnotheres*) live in the mussel shells, robbing the mussels of their food and gaining shelter. On the

mussel shells may be found a great many creatures, like the little worm *Spirorbis* in its tube of lime or polyps, sea-mats or other encrusting animals, not to mention the tufty growths of the sea-lettuce (*Ulva*) that find a foothold there. All fixed and slow moving animals are liable to be settled upon by the larvae of others and by the spores of seaweeds. Hence it comes about that crabs often trail around a little forest of growing things upon their backs which they can only get rid of when they cast their skins. Sometimes such growths are useful to the crab and help to hide it in the bushy glooms where it lives. The spider crab (*Inachus*) is even believed to place pieces of weed and polyp colonies on its back in order that they may take hold there. If this is the case then this is more than a mere casual association, for both the crab and its vegetable or polyp partner derive some benefit from it—the crab gains concealment and the weed or polyp the advantage of being continually carried about. This is, in fact, what is known as commensalism—a partnership for mutual benefit. The seashore can show many much more elaborate instances of this than the crab with its trailing growths. The classical example is that of the hermit crab (*Eupagurus prideauxi*) which lives in the empty shell of the whelk. On the shell grows an anemone (*Adamsia palliata*) which conceals the crab and, as a reward, is fed with scraps which do not fall but rise from the rich man's table. An even more curious mutually beneficial partnership is that between the little tropical crab (*Melia tesselata*) and the anemones which it carries about in its claws. It holds them out fully expanded, pushes them forward as weapons when attacked, so as to bring their batteries of stinging cells into action in its defence, and takes food

out of their mouths. The crab's claws are specially modified for this purpose and are unable to fulfil any other function. The advantages of this arrangement to the crab are obvious enough and the anemones, one must suppose, gain a mobility they would not normally possess to compensate for the loss of part of their food. From this kind of association for mutual benefit, which is not much more than active or passive neighbourliness, the next step is to a more intimate form of partnership altogether in which two distinct living beings, it may be totally unrelated, enter into a close physiological relationship with one another. This kind of intimate relationship, which is not merely of mutual benefit but essential to the existence of each partner, is known as symbiosis—literally, life together. There are many examples of it on the seashore. Many sponges, hydroids, anemones, corals and flat-worms contain microscopic green or yellow plant cells, the Zoochlorellae and Zooxanthellae, which live in their tissues. Neither the animal nor the plant can live apart. The animal benefits from the products of the photosynthesis of the plants and the plants from the waste products of the animal. The best known case of symbiosis on the seashore is that of the little flat-worm *Convoluta*, which lives on sandy shores on the coast of Brittany. It is a little bright green worm a few millimetres in length and it appears in brilliant green patches on the sand as the tide retreats. Just before the tide returns, the Convoluta sinks into the sand again. This regular habit and the bright green colour are due to the presence in the tissues of the worm of great numbers of single green plant cells which live just below the surface of the skin. The worm does not start life with these green partners but soon after the egg

begins to develop it becomes infected with them and, if prevented from doing so, it fails to develop and dies. In early life, too, the worm can feed like other flat-worms on diatoms, spores and microscopic debris, and has a mouth and a digestive canal for the purpose. These later degenerate for the worm finds it easier to live on the starch produced by the photosynthesis of its zoochlorellae. In order that this photosynthesis may go on in its body the animal must expose itself to the sun and so it lies on the sand all the hours that the tide is out. But it must sink into the sand as the tide comes in again in order not to be washed away.

There are, however, on the seashore, as in every other realm of life, many associations in which one member definitely preys on the other and gains a living at its expense though seldom, for obvious reasons, to its destruction. These are the cases of true parasitism and for the parasite to destroy its host is to destroy itself. Therefore, although the host is always sickly and in poor condition on account of the presence of its unwelcome guest, it seldom dies because of it. Parasitism may range from an association involving a mere juxtaposition, in which one member benefits at the expense of another, to an intimate physiological relationship. In extreme cases, the parasite degenerates, losing all shape, all sense organs, all power of locomotion and may become merely a digestive and reproductive system inside but alien to the host. The little pea crab illustrates the first kind of parasitism for it lives in the shell of the edible mussel, sitting on the curtain-like gills and scooping up into its mouth the threads of mucus and the food particles they normally carry to the mussel. Here the pea crab definitely robs the mussel of food and gains

shelter from its shell but does the mussel no other harm. But the sac-like barnacle parasite *Sacculina* (Fig. 8) of the common shore crab is a very different affair. Many of the shore crabs found in late summer have a soft bag of tissue hanging under the body, between the small tail

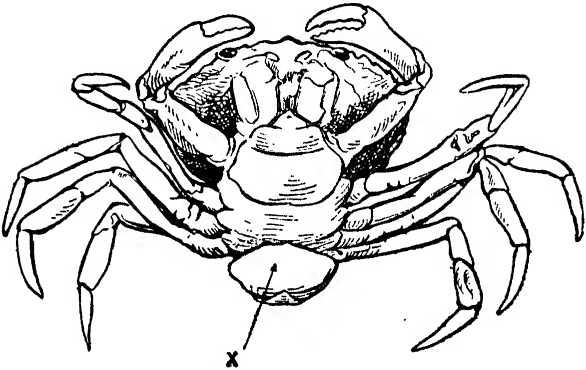

FIG. 8. Crab infected with the Sacculina parasite (X).

of the crab and the broad thorax. The bag is nothing more nor less than a barnacle, no matter how little it may look like one. It begins life as a nauplius larva which subsequently becomes a little bivalved larva (the cypris stage) just as a barnacle does. The cypris stage attaches itself to the base of a bristle on some suitable and vulnerable part of the crab's body. It penetrates the soft skin at the base of the bristle by means of a special boring organ, casts off its legs and gets into the crab's blood stream. It reaches the underside of the crab's intestine and from there sends out branching roots

into every part of the host's body. It grows larger and larger, pressing against the underside of the body wall. When the crab next moults the parasite pushes its way through the soft skin and appears on the outside as a bag, like a tumour, consisting solely of a sac which contains the reproductive cells. The barnacle has now no organs except this sac of reproductive cells and the ramifying roots that absorb nourishment from every part of the body of the crab. It has no other shape but this and no powers of movement, no sense organs. From the time that the parasite appears on the outside of its body the crab never moults. It becomes sluggish and inactive and all its food goes to nourish the intruder which may live for three or four years. But the most astonishing feature of this extreme case of parasitism is the fact that male crabs change their sex and become female as a result of it. They change their shape, developing a broader tail and smaller claws and sometimes even producing eggs. But female crabs thus afflicted do not become males. The theory is that the sluggish sedentary habits that the parasite imposes on the male crab, owing to lack of nourishment, induce this change of sex, the roots of the barnacle affecting the physiology and life processes of the crab in the same way that an ovary normally would.

There are many other examples of parasitism, more or less extreme, to be found on the shore. Various copepods, which resemble copepods in their final stages hardly more than the Sacculina resembles a barnacle, inflict themselves upon fish and upon sea-slugs. Some of these are the fish lice which attach themselves to the gills or to the soft skin around the eyes of fishes or cling to the outside skin of the body. The females are

often more extreme in their degeneration of form than the males. They may be more like worms than crustacea and carry very small males attached to their degenerate and misshapen bodies. Some (*Lernaea*) consist of little more than a bag of reproductive cells. Others cling to the fish by means of suckers and can move about over the skin.

All these are the freakish results of an intense struggle for existence in which food is the most important and pressing consideration. The next most important is living space, which is a function of the available food supply, and this again largely determines the vast variety and ingenuity of methods of reproduction on the sea-shore. The same bitter struggle and fierce competition for the necessities of life has led to a great diversity of methods of attack and defence, methods of concealment, warning and protective coloration with which there is no space to deal here. We must leave this battle ground between the sea and the land, with its exquisite balances and adjustments, its profligate waste, its eternal death and decay and constant renewal, and move farther out beyond the last line of rollers where the ribbon weeds lift up in the green walls their strands like mermaids' hair, to a world darker and more still and even more mysterious.

CHAPTER VI

THE CONTINENTAL SHELF

Conditions of life in the shallow water zone—The benthos—Sponges—False corals—True corals and coral forming organisms—Coral reefs—Fringing reefs, barrier reefs and atolls—Theories of reef formation—Darwin, Murray and Daly—The Funafuti boring—Echinoderms—Distribution of the fauna of the shallow-water zone.

THE ZONE of shallow water extends from the level of the lowest springs to the hundred fathom line, which Murray called the mud line because, roughly, it marks the limit of the coarser sediments washed down from the land. Very approximately, too, this line is taken to mark the edge of the continental shelf where it steepens into the continental slope. It is a zone with special characteristics for, as already described, it is the neritic zone where the sea is enriched by salts washed out of the coastal rocks or carried down by rivers, where salinities and densities fluctuate because of the addition of fresh water, and where the light of day penetrates down to the bottom. Nevertheless the conditions of life in it are more stable than they are in the tidal zone and changes in temperature and salinity are less abrupt and smaller in range. It is a zone, too, where water wells up from below against the continental slope so that a constant renewal of nutrient salts goes on. Because of this its plant life, both fixed and floating, both the seaweeds and the plant plankton, is richer than it is out at sea. It supports a

large and varied animal plankton, both permanent and temporary, different from that of the open ocean and it is the home of an immense and varied benthos population. From the low tide mark out to the continental edge or mud line the bottom gradually passes from coarse sand and rocks to fine sand and then to the finest muds. It shows a more or less definite linear grading from the laminarian zone to the continental edge, from the stones and gravel to the mud. The nature of the ground determines the kind of bottom-living population in the shallow water zone as much as it does between the tide marks, for each type of bottom has its own fauna and, as a result, there is a certain amount of linear zoning of living things below the low tide mark as above it. Further, animals seem to be extremely selective with regard to the kind of bottom they live upon. This is easy enough to understand in many cases. It is obvious that an animal adapted for burrowing in mud, like the sea-cucumber (*Holothuria*), will choose that type of ground, or the masked crab (*Corystes*), which lives in sand with its antennae projecting so as to form a breathing tube, will obviously choose a fine clean expanse of sand not often disturbed. But many animals seem to exercise a degree of choice which is less easy to understand. The Norwegian lobster (*Nephrops norvegicus*) lives on mud in many parts of the Irish Sea, but seldom ventures on to the neighbouring sandy patches. The circular crab (*Atelecyclus*), on the other hand, is found neither on sand nor on mud but on coarse sandy gravel. Much less is known about the habits of the animals that live on the continental shelf than about those of shore animals. The former can only be seen when they are scooped up in a dredge, wrenched from

their still depths, torn up, as it were, by the roots; whereas the latter can be studied in their homes. When more is known about them it will no doubt be found that their choice of bottom depends on their food, their burrowing powers and their method of breathing. There is, of course, a great deal of overlap and there are many animals that are more or less indiscriminate in their choice of ground, like the bristle worms which are abundant almost everywhere in salt water, or the sea-urchins and starfish which are found on almost every kind of bottom.

The bottom of the shallow water zone provides every kind of substratum for the temporary plankton to settle upon or for the adults to creep over or burrow into. Hence the great richness and variety of the benthos. The conditions of life are quiet and still, free from the wash of waves and fast moving currents, so that in addition to all the animals that can be found between the tide marks, many of which, like the anemones, achieve great size and profusion, there are also abundant growths of fragile branching things like corallines, sea-fans and dead men's fingers. Great sponges and squirts also form thick masses on the bottom. The sea-mats form their brittle trellises and the lamp shells grow in clusters like large grapes. All these in turn provide shelter for innumerable creeping things, molluscs, crustacea and worms. The oozy mud is a home for molluscs, like the clam and the whelk and the heavy black *Cyprina islandica*, and for bristle worms and tube-living worms of many kinds. The tube-living worms particularly reach a great size and matchless beauty, holding out their feathery whorls in the dim twilight. Lobsters, spider crabs, fantastic crustacea like the glass prawns (Galatheidae)

and the mantis shrimp (*Squilla*) and octopuses live among the rocks.

This varied bottom living population thins out beyond the continental edge. This is not because the water becomes too deep or too dark or too cold, or because the pressure becomes too great, for none of these conditions prohibits life. It is because in the deeper water beyond the continental shelf the dead bodies of plants and animals, raining down from the plankton above, only reach the bottom as skeletons or empty shells. All the tissue has been dissolved out of them long before they reach the end of their downward journey. On the continental shelf, however, the decaying tissue in the rain of falling bodies continually manures the sand and mud of the bottom. The death and decay of the benthos population itself contributes to this continual fertilization of the ground. Burrowing molluscs and worms churn up the fine sediments and pass them through their bodies, reducing them to an ever finer and finer state, so that they form organic food material for bottom-living animals. But more than this, the bottom beyond the continental shelf is too soft and impalpable for any but very specially adapted creatures to live on it. There is, indeed, some life even in the very deepest waters of the ocean but, as we shall see later, it is of a special kind and sparse in amount. Life is a self-renewing process and the abundance of life in the shallow water zone is both the direct cause and the result of its own profusion, for the death of millions provides food for the millions of the living. The plant and animal life, decaying and excreting in the shallow water zone and along the shores, both enriches the water with nutrient salts and, more directly, provides food for bottom-living animals.

The abundance of the benthos on the continental shelf makes it the region of the richest fishing grounds. It is, in fact, the principal home of the nekton, and here live the food fishes which, from the point of view of the health, wealth and happiness of mankind, are the most important of all the living communities of the sea. Yet before we deal with them we must say something of the more humble forms of life upon the continental shelf.

In the tidal zone we found small encrusting sponges clinging to the rocks such as the bread crumb sponge (*Halichondria panicea*) or the little purse sponge (*Grantia compressa*). But below the low tide mark the sponges reach a much larger size and form amorphous growths or strange and beautiful shapes. Curiously enough the sponges are quite definitely animal in their organization, though they are indeed among the simplest and lowliest forms of animal life. The simplest kind of sponge consists of a hollow vase moored to a rock or seaweed by one end (Fig. 9). The wall of the vase is lined by cells, each with a stiff collar of protoplasm directed into the cavity of the vase. From the centre of each collar a whip-like thread agitates ceaselessly, drawing in water through innumerable holes in the wall and driving it out through the mouth of the vase. The cells are, to a considerable extent, independent of each other and if the sponge is chopped up into fragments the separate pieces, no matter how small, can reconstitute themselves into a new and perfect sponge. The outside of the wall has a flat layer of cells forming a skin and, between this outer layer and the inner one of collar cells, is a clear jelly in which needles of lime or silica are embedded. In the jelly irregular cells wander about quite independently and, in the summer, they enlarge to form eggs or divide

to form motile sperms. There are, however, many elaborations of this simple pattern. In some the vases bud off others and these join and ramify so as to form a complicated system. In others, again, the wall of the vase may be reduplicated so that the inner collar cells are enclosed in chambers which communicate with the

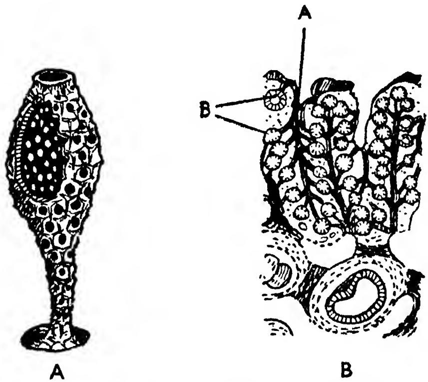

FIG. 9. (*a*) The Olynthus stage in the development of a calcareous sponge, illustrating the simplest type of sponge. (*b*) Section of a more complicated type of sponge showing the inhalant canals (A) and the flagellate chambers (B), &c.

outside and with the main cavity of the vase by means of a complex system of canals (Fig. 9). The water then flows gently in at the smaller inhalent openings in the wall of the sponge and more strongly out at the larger exhalent ones. In the bath sponge the system is exceedingly complicated but, in general, the small holes are the inhalent pores, which in life draw the water inwards, and the larger holes are the exhalent pores by which the water flows out. Most sponges have a skeleton which,

in the bath sponges, is made of a fibrous horny substance called spongin. It fills all the substance of the jelly wall and, when the living sponge is first brought up from its home on the bottom, the skeleton of fibres is covered with the black slimy living tissue of the outer layer of skin cells, which must be dried off. But a far greater number of sponges have a skeleton made of beautiful and complicated spicules of lime or silica embedded in the jelly. They vary in shape from little straight needles to stars with three, four or six rays, or they may have the shapes of hooks or anchors.

The bath sponges live mostly in the Mediterranean, especially in the Eastern half, off the coast of Florida and off the Bahamas. But very many sponges are found all over the world from the high tide mark down to the greatest depths. On the shores the encrusting bread crumb sponge has a skeleton consisting of spongin fibres together with needles of silica while the little purse sponge is of a simpler type and consists of a little perforated vase hanging by a stalk. But in deep still water the sponges assume beautiful and fantastic shapes, like urns or baskets or amphora, incredibly delicate and lovely, made of fine interlocking needles and hairs of glass. The deep sea glass sponge (*Pheronema*), which comes from deep water beyond the mud line, is an oval basket woven of fine needles and at one end of it is a great cushion of matted glass hair—all very difficult and painful to handle for it leaves thousands of its broken spicules behind in your hands.

The rocky or stony bottoms of the shallow water zone are covered with tree-like branching growths, the red sea-fans, with an intricate lace-work of calcareous

branches all spread in one plane like a fan, or the white bulbous dead men's fingers. All over their branches they bear thousands of delicate polyps like anemones. They are, in fact, colonial anemones based on a common skeleton, which is made of lime in the sea-fans, but of a spongy matrix containing a mass of delicate spicules of lime in the dead men's fingers. In both sorts of colony the skeleton is covered by a film of flesh which unites the bases of the tentacled polyps so that, when the growth first comes up in the trawl, it is smooth and slimy. It is smooth also because the tentacles are withdrawn into pockets and only when they are covered in still water do they expand like flowers all over the branches of their stony tree.

These are the false corals—so called because they do not form reefs in temperate latitudes but cover many square miles of the continental shelf with their stiff undergrowth. The red precious coral, from which necklaces are made, lives in the Mediterranean and is more nearly related to the sea-fans of our waters than to the true corals of the reefs and atolls.

In shallow seas around our coasts there lives among the rocks a single true coral (*Caryophyllia*)—a little solitary anemone which secretes round itself a calcareous cup about half an inch in height. The stony skeleton penetrates into the polyp so as to form thin sheets supporting the many partitions which almost, but not quite, completely divide the body cavity. The true stony corals, the Madreporaria, which build up the largest part of the coral reefs of the tropics, are the same as this little solitary form but multiplied many millions of times by the repeated division and re-division of the original polyp in its cup. As the new polyps form, the old ones die

and great masses of limestone accumulate, growing outwards but never upwards just below sea-level. In this way ribbons of coral rock are formed along the tropical coasts, like rings round islands or as those ring-shaped, palm-fringed atolls, enclosing lagoons, which are the enchanted gardens of the Pacific.

The Madreporaria, or true corals, however, are not the only creatures that build coral reefs. A very common form is the stinging coral (*Millepora*) in which each polyp is surrounded by a circle of little stinging tentacles, modified polyps, whose function is to capture and paralyse minute prey for the larger central polyps to devour. The Millepora make a thick skeleton of lime and the polyps project through minute apertures in its outer surface. They increase by continual branching and budding but they also show alternation of generations, giving off clouds of little circular swimming bells bearing eggs and sperm.

Several of the false corals, related to our sea-fans, are important builders of coral reefs. One of these is the bright red organ pipe coral. The green polyps of this lovely form live in cylindrical tubes. Each polyp grows vertically upwards and, when its cylinder reaches a certain length, it secretes a horizontal plate across the tube at its base and thus seals off an empty compartment below itself. It then grows upwards again and, in due course, seals off another compartment until the whole colony comes to resemble the vertical pipes of an organ divided by regular horizontal partitions, like the floors of a skyscraper building, with the green tentacled polyps occupying the top floor.

Many calcareous plants also take part in the formation of reefs, forming encrustations on masses of dead coral

or on rocks, binding the whole mass together. These are the Nullipora, of which the Lithothamnion, known to us from our own continental shelf, is the commonest. There is also the green calcareous plant *Halimeda*, which grows all over the reefs and has fronds made of calcareous discs with limy joints. In addition the whole mass may be bound together by crystalline carbonate of lime, dolomite, deposited out of solution by the sea water.

The corals are exceedingly sensitive to the conditions under which they live. They cannot stand temperatures lower than 68° F. and are therefore restricted to a tropical belt between 25° N. and S. latitude. For the same reason, and owing to the temperature distribution in the oceans, most of the coral reefs are found on the western sides of the ocean basins. The polyps feed by ingesting small plants and animals which they capture with their tentacles. They must live, therefore, in water which is in motion. But many of them have added another and stranger mode of feeding to this. Nearly all corals, but some more than others, live in symbiosis with little single-celled green plants which inhabit their tissues, especially around the mouth and tentacles, and are often numerous enough to give the polyp a green colour. If, for any reason, its normal food becomes short, the polyp extrudes these plant cells into its body cavity and feeds on them. In some corals, indeed, the polyps depend absolutely on these plants, which block up the stomach cavity with their green masses, so that the polyps are no longer able to feed in the ordinary way at all. It seems that corals which have these plant cells in their tissues cannot live without them and, for this reason, are obliged to live in shallow water, within about thirty fathoms, where bright sunlight illumines the water

so that their plant guests can carry on their essential photosynthesis. There are, however, corals which live at greater depths than this but these do not have the green plants in their tissues.

The action of waves has a very great effect in shaping the growth of corals. In calm water they form beautiful branching growths like the stag's horn coral, which resembles the antlers of a deer as its name implies. But violent wave action, by continually breaking off the tips of the growing branches, gives to the masses a rounded outline like a much clipped hedge. Sediment, too, plays a very important part in shaping them. The lower polyps in a coral mass are sooner or later killed by silt raining down upon them from the growth above and, in large rounded masses, the central polyps are suffocated by gathering sediment while those outside go on growing so that the cushion becomes a flattened plate with irregular edges of growing coral. The coral masses themselves are all the time being broken down into fine sand and rubble. Waves break off pieces and throw them on to the top of the reef. A continual rain of debris rolls down the slopes of the reef into deeper water and countless animals, boring molluscs and fish with parrot-like beaks (Scaridae), break up the coral rock. Great sea-cucumbers a foot or so in length swallow the rock and reduce it to sand within their bodies, throwing up casts like those of the lugworm.

At first sight a coral reef seems uninteresting enough—a mere greyish expanse of gnarled dead-looking coral rocks shading into fine white sand. But in the deeper channels and pools, and on the seaward slopes of the reef, there is a world of colour and fantasy where the living corals open their hearts to the clear light. The

prevailing tints of corals are yellowish, pinkish brown and rose pink with here and there a note of contrasting brilliance. The polyps themselves may be of many colours, green or yellow, violet, pink or white. Among the corals, shoals of brilliant blue and yellow fish weave in and out. The giant anemone (*Stoichactis*), with prussian blue tentacles, the red and purple crabs (*Trapezia*) and many other animals with contrasting and dazzling colours make the region of living corals one of unimaginable delicacy and beauty.

There are three types of coral reef. The first type is the fringing reef which lies just off the main shore, separated from it by a narrow and shallow lagoon. The second is the barrier reef, which lies at a much greater distance from the coast. It may be several miles wide with innumerable channels through it, with shallow lagoons and here and there a wide steamer passage. A wide channel safely navigable by ships separates the barrier reef from the coast of the mainland. The most famous reef of this sort is the Great Barrier Reef of Australia, which is over a thousand miles long from New Guinea to about two-thirds the length of the coast of Queensland, from 9° S. to 22° S. latitude. In its northern half the barrier may not be much more than twenty or thirty miles from the coast but in its southern half, off the Queensland coast, it is as much as fifty or a hundred miles from the mainland and consists of several parallel reefs with channels between them. The third kind of reef is the atoll, a ring of growing corals, crowned with palm trees, often hundreds of miles from any true land and rising abruptly from thousands of fathoms. In the middle of the broken coral ring lies a lagoon fifty to seventy fathoms deep. As you approach the atoll from

the sea the palm trees sometimes appear to be standing in the water and it seems miraculous that the white rollers do not run right over the silver strip with its narrow green band into the still lagoon it encloses.

The formation of the fringing reef is fairly easily explained, but how the barrier and the atoll come to be formed still remains something of a mystery and a subject for discussion. To explain the fringing reef (Fig. 10) we must suppose that at some time in past ages the coastline had no corals growing on it. They established themselves along the thirty fathom line and grew upwards and outwards. Upward growth, however, ceased when the reef reached the low tide level because coral polyps cannot stand long exposure, but outward growth continued, carrying the line of living coral away from the coast. As the reef grew the sea would be continually breaking pieces off and throwing them up on top of the reef where they would become broken down into sand. At length vegetation, borne thither by seeds carried by birds and floating wood, would grow and bind the coral rocks together and form a subsoil by its decay. Pieces broken off above, too, would be continually rolling down the steep slope to seaward, together with silt and debris, and this would eventually make a foundation on the bottom for the further outward growth of the reef. The greatest growth takes place near the surface and decreases steadily to the thirty fathom line, ceasing below that. The slope of the outer face of the reef, therefore, steepens slowly as growth goes on until at last it becomes a precipitous underwater cliff, starred with its myriad polyps like daisies in the bright sunlight just below the surface. Meanwhile a shallow trough is formed behind the reef between it and the coast. The formation of the lagoon

between the coast and the reef is still not fully understood but it is thought that it may be caused, in part, by the disintegration of the rock by animals, by the scouring action of the waves rushing through or over the reef and by direct solution of the rock by sea water. None of these explanations, however, seems quite adequate at present. As the reef grows away from the shore the lagoon receives the debris washed away both from the reef and from the coast and brought down by rivers from the mainland so that in time it comes to have a flat bottom of silt. If the lagoon is deep and clear enough the corals begin to grow again on the inner side of the reef and so narrow down the lagoon or even fill it up.

The formation of barrier reefs and atolls has been a subject for dispute since Darwin first put forward his classical theory based on his observations during the voyage of the *Beagle*. Darwin's theory is extraordinarily simple. It implies that over the whole extent of the coral seas the sea floor and the projecting land have been slowly subsiding for many millions of years. This gradual sinking has been either continuous or by stages but its rate must have been slower than the rate of upward growth of the corals. As the land sank, fringing reefs based on it grew continuously upwards and outwards (Fig. 10*a*) and were converted into barrier reefs, so that finally, around sinking islands, only a coral ring, based on a submarine peak, remained to show where an island once had been.

At the end of the last century and the beginning of this, one serious objection to Darwin's theory was raised. It was thought that the mere existence of atolls was insufficient evidence, by itself, for such widespread sinking of the land as the theory implied. Indeed it seemed that

in some areas coral reefs had actually been raised up as, for instance, in the Pelew Islands where there are coral reefs which seem to have been lifted some 400 to 500 feet. There are places, too, where fringing and barrier reefs and atolls all exist together. Accordingly Sir John

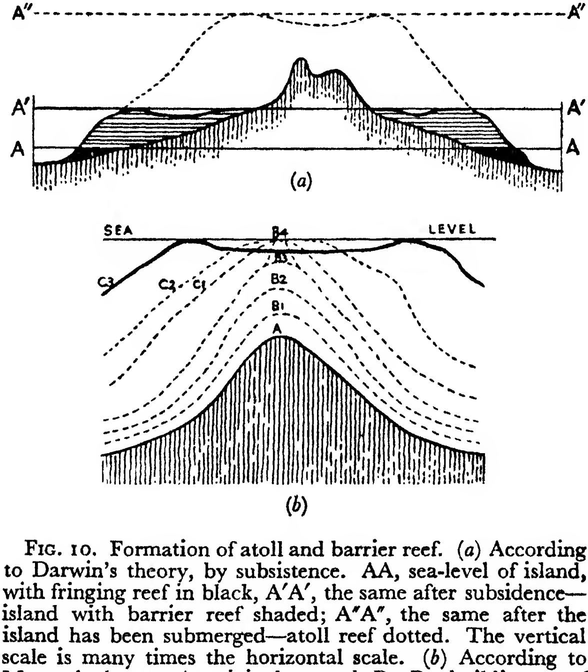

Fig. 10. Formation of atoll and barrier reef. (*a*) According to Darwin's theory, by subsistence. AA, sea-level of island, with fringing reef in black, A′A′, the same after subsidence—island with barrier reef shaded; A″A″, the same after the island has been submerged—atoll reef dotted. The vertical scale is many times the horizontal scale. (*b*) According to Murray's theory. A, original mound; B1–B4, building up of same by remains of deep-sea animals, by pelagic deposit, and by reef organisms at sea-level, C1–C3, outward extension by accumulation of talus and other materials on the slopes and further growth of reef organisms; hollowing out of the surface by solution and removal of mud in suspension.

Murray put forward an alternative theory. His idea was that the barrier reefs resulted from the continuous outward growth of the fringing reefs, spreading outwards on the foundation of their own rubble, while the lagoons were enlarged by the solution of the coral rock. Atolls, he thought, were crowns of coral based on submarine peaks (Fig. 10*b*). These peaks, he realized, could not necessarily all be of the same height but those which did not rise to a height sufficient for coral growth would be raised to the appropriate level by submarine deposits laid down on their summits. On the other hand, those which had risen beyond the coral level had been cut down by the action of waves. The lagoons, again, had been hollowed out by solution of the inner part of the coral crown. This theory gained a wide acceptance but there are, nevertheless, many objections to it. In the first place all atolls descend very steeply on their seaward faces to depths of thousands of fathoms and it is difficult to see how submarine deposits could ever have been laid down on a base at such a steep angle. Furthermore, sea water has in fact only quite a small dissolving action and it seems unlikely that the lagoons, could have been formed by solution either behind reefs or in the middle of atolls. If, again, the dissolving action of the sea water were sufficient to hollow out lagoons, surely it would also be sufficient to dissolve away the deposits which were supposed to build up the submarine banks on which the atolls grew. The lagoons behind the fringing reefs would more probably be filled up by silt brought down by rivers from the land, or broken off the reef, faster than they could be hollowed out by solution.

The great Alexander Agassiz suggested that barrier reefs had grown up on platforms cut down by wave

action along the coasts of continents and around islands This, he supposed, would account for the fact that all lagoons have a uniformly flat bottom.

Professor Daly of Harvard, in 1915, advanced a still more ingenious and totally different theory, known as the theory of glacial control. He supposed that all modern coral reefs had been formed since the Pleistocene, that is, the most recent, ice age. At that time vast fields of ice were formed in the northern and southern hemispheres, so that enormous volumes of water were locked away as ice and, as a result, the general level of the ocean sank some thirty or forty fathoms. There was also a lowering of the temperature of the sea over the whole world so that large areas of the coral seas became too cold for the growth of corals. Many coral reefs, therefore, died during the Pleistocene ice age either by exposure on account of the lowering of the sea level or through the drop in the temperature of the sea water. The new sea level then cut platforms or benches along the coasts and around islands. When the ice age came to an end and the ice melted the sea level rose again, submerging these newly cut benches and platforms again to a depth of thirty or forty fathoms. On the seaward edges of these the corals established themselves anew by the proliferation of those that had not been killed, thus building up fringing reefs, where the submerged platforms were narrow, and barriers, where they were broad. Atolls would be formed on the tops of peaks cut down during the ice age. This theory would account for the flatness of the bottoms of the lagoons and it was argued that it would also account for the fact that all lagoons, both behind reefs and in the middle of atolls, are of approximately the same depth. However, it has

since been shown that there is, as a matter of fact, quite a wide variation in the depths of lagoons in different places, between 50 and 100 fathoms.

At the end of the last century the discussion centred round the theories of Darwin and Murray. Many naturalists and geologists supported Darwin's theory, involving large scale sinking of the land, while many others supported Murray's idea of reefs growing on stable foundations. Finally it was decided that the only way to settle the question was to make a boring through a coral reef. If Darwin's theory were correct, then a boring of several hundred feet would fail to reveal any rock base beneath the coral, but if Murray's theory were correct, then somewhere about thirty or forty fathoms down the boring should strike a rock foundation. Accordingly in 1896 an expedition, sponsored by the Royal Society and headed by Professor Sir Edgworth David and Professor Sollas, went to the Pacific and made a boring on the atoll of Funafuti. The boring reached a depth of 1,114 feet 6 inches. For the first 750 feet of its length it passed through powdered coral rock with, in the surface 150 feet, coral masses and encrusting Lithothamnion in the positions in which they grew. The rest of the core consisted of compacted and crystallized limestone which had resulted from the compression and transformation of the coral rock into a crystalline carbonate of lime known as dolomite. Nowhere was any rock of volcanic origin found. It might have been thought, therefore, that this proved the truth of Darwin's theory but the other side pointed out that the boring had been made, unfortunately, at the edge of the atoll and claimed that it had passed through the rubble foundation, the talus of compacted coral rock, on which the reef was built.

Agassiz, indeed, suggested that the compacted rock at the bottom of the boring was in fact a foundation of tertiary limestone. Accordingly it was held that the result of the Funafuti boring was inconclusive and might be taken as evidence for either point of view.

Of late years, however, opinion has swung in favour of Darwin's grand and simple ideas. One of the facts that seem to point to a subsidence of the land in coral seas is the gentle slope of all coastlines behind fringing and barrier reefs. The hills slope gently down to the lagoon unbroken by any cliffs. The bays are of the type which geologists term drowned valleys with floors of sediment washed down by rivers. If the reefs stood on platforms worn by the action of the sea, as Murray and Agassiz supposed or as Daly imagined in his glacial control theory, the coastline would have quite a different appearance. It would present steep cliffs fronting the lagoon and there would probably be no islands along the coast. But, in fact, not only are cliffs of any size never found behind coral reefs but there are often rounded islands dotted about in the lagoon as there are in the channels between the coast and the Great Barrier Reef. Then again, if we picture the land as stationary with the coral growing outwards as a thin veneer on a submarine platform, it is difficult to see why the lagoon does not become filled up by sediment carried down from the land by rivers. Further, it is not now believed that sea water can possibly have enough dissolving action to hollow out lagoons either behind reefs or in the centre of atolls. But if the land is sinking there is no reason why the lagoon should ever fill. There is even a tendency now to think that the Funafuti boring may, after all, support the Darwin theory since it has been pointed out

that the re-crystallization of coral rock into dolomite is a process which can only take place in quite shallow water. Further, all the coral remains found throughout the core were those of shallow water forms and it has now been established that the compacted rock at the bottom of the core was not a tertiary limestone, as Agassiz suggested, but had resulted from the compression of the coral rock itself. Another boring made by the Great Barrier Reef Expedition of 1928–9 at Michaelmas Cay, near the town of Cairns, showed nothing but loose coral rock and sand throughout the 600 feet or so of its length.

Nevertheless the formation of coral reefs still remains something of a mystery. Darwin's theory is by no means proved. But it is believed that the seismographical observations made during the recent atom bomb test at Bikini tend to confirm it. Plans are being laid for more and deeper borings which, it is hoped, will provide the answer to this riddle, now a century old.

After this digression into the tropics we must return to the shallowwater zone around our own islands. A stiff branching forest, made up of many different kinds of creatures, many of them colonial, covers the hard grounds, the stony and rocky bottoms on the banks, where the vast benthos population lives and shelters. It consists, as we have seen, of the false corals, the sea-fans and the dead men's fingers, and, in addition, many other creatures which, between the tide marks, are found only as encrustations on rocks, on stones or on the fronds of seaweed. These include the sponges and the sea-mats which grow up into erect branching growths, and the rounded or branching masses of the calcareous coralline alga *Lithothamnion*. Along the low tide mark this encrusts

the rocks and forms a foothold for the ribbon weed but below the low tide level it forms masses with elaborate branches or rounded clumps according to the amount of wave action to which it is exposed. Large sea squirts also live on the hard bottom, like leathery double-necked bottles or tough formless masses.

On the continental shelf the echinoderms are a group of very great importance. This is the group which includes the starfish, the sea urchins, the brittle stars and the sea-cucumbers. Some, like many of the urchins, live among the rocks. Others again, like the brittle stars and sea-cucumbers, live on sand and mud, but all are fairly catholic in their choice of ground and may be found almost anywhere. Most of them creep about on the bottom but a few have some power of swimming, like the feather stars (*Antedon rosacea*). In spite of the great variety of their appearance they are all built on the same radial plan within a skeleton made of plates or spicules of lime and five—or some multiple of five—radial arms radiating from a central disc. They all have the extraordinary water vascular system forming a ring within the central disc with branches along the arms. The starfish and the urchin move upon thousands of delicate inflated processes of this system of water tubes, known as the tube feet, each like a minute fountain-pen filler. When the feet are withdrawn the bulb of the filler, which communicates with the vascular system, is filled with fluid. It is emptied when the feet are rigidly protruded.

On the soft grounds of the shelf the stiff branching forests are missing, though many of the large sedentary softer creatures are still found in abundance. There are plenty of sponges and squirts. But this is the home of many burrowing and tube-living creatures, those which

we found between the tide marks and many others besides. On the continental shelf, however, the difficulties that arise between the tide marks from the constant shifting of sand or mud, or from its exposure by the tide, naturally form a less important factor for animals that burrow or live in tubes upon the bottom. Delicate worms, which secrete their own tubes and project from them exquisite crowns of feathery tentacles, therefore reach a great size in these quieter and more stable conditions. The anemones, too, whether they live on a rocky or gravelly bottom, reach a magnificent development which is never seen between the tide marks. Molluscs are incredibly abundant on the soft bottoms. Large coiled snails such as the whelk are found in great numbers and a bivalve (*Spisula subtruncata*), like a small cockle, occurs in patches many square miles in area with a density of thousands to the square yard on the Dogger Bank, where it is the food of the plaice.

While purely local variations in the population of the continental shelf may occur in accordance with the nature of the bottom, yet the major influence, as in the open ocean, which causes large scale changes in the character of the population, is exercised by the temperature of the water. Many shallow-water animals are world-wide in their distribution but many of those which live at fairly shallow depths in temperate or polar waters are found at greater depths in the tropics where the shallow water becomes too hot for them. However, a general similarity of the shallow-water population in certain parts of the world has made it possible to mark the world out into geographical regions with respect to the inhabitants of the continental shelf and tidal zone. There is an Arctic and an Antarctic region. The Arctic

region is divided again into a circum-polar region, which embraces Greenland, the northern coasts of Europe, Asia and North America, and an Atlantic-Boreal region, including the west coast of Europe and the east coast of North America. Similarly there is a Pacific-Boreal region embracing the northern shores of the Pacific from Japan to California. The Antarctic region includes the southern coasts of the continents bordering the Southern Ocean. In the tropics there is an Indo-Pacific region, covering all the shores of the Indian Ocean, all the coasts of the Indo-Pacific islands and the northern coast of Australia. There are East and West American regions and a West African region. There is, of course, no hard and fast line of demarcation anywhere between the populations of these great areas. They overlap and shade gently into one another. Further, their populations tend to resemble each other along, rather than across, the lines of latitude, that is to say, the changes in the shallow-water population are greater from north to south than from east to west just as we found, indeed, in the plankton population of the open sea. For instance, the fauna of the shores of Canada and the United States is far more like that of the coast of Europe than that of the West Indies and the fauna of East Africa far more closely resembles that of India and the Pacific than it resembles that of South Africa. The similarity of the West African population to that of the east coast of South America is so close that it is used as an argument for supposing that at one time the two continents must have been united by a bridge of land, the Gondwanaland continent.

CHAPTER VII

THE ABYSS

The continental slope—Submarine canyons—The abyssal plain—Terrigenous deposits—Pelagic deposits—Globigerina ooze—Pteropod ooze—Diatom ooze—Red clay—Radiolarian ooze—Conditions of life in the great deeps—Deep sea fishes—Deep sea benthos.

THE CONTINENTAL SHELF inclines gently, with an average slope of about one in five hundred, to the hundred fathom line. Thereafter, though beginning usually at a slightly smaller depth than a hundred fathoms, the slope of the shelf steepens at the continental edge to an average slope of about 1 in 10 or 1 in 15. This is the continental slope which plunges down into the deep sea, to the abyssal plain, where the depth is between 2,000 and 3,000 fathoms.

It was at one time thought that the continental slope was a smooth inclined surface slanting down into the abyss, a talus slope like the even sides of a mine tip. But as soundings, taken by the modern echo sounding method, have increased in numbers all round the coasts of the continents, it is beginning to be realized that the surface of the slope is everywhere carved into canyons and gullies, with sharp ridges between them, running at right angles to the coasts. The larger of these canyons head far back from the continental edge and form deep grooves in the surface of the shelf, some of them continuous with the mouths of rivers. On the coast of Europe most of the principal river courses run outwards

over the shelf as steep sided canyons such as this and the best known, perhaps, is the Fosse de Cap Breton, opposite the mouth of the river Adour, which opens into the Bay of Biscay near Biarritz. Near the mouth of the river the bottom of the channel is 117 fathoms below the general surface of the continental shelf. Farther seaward it becomes a rock canyon 500 to 1,000 fathoms deep and opens at the foot of the continental slope 1,500 fathoms below sea level. Its sides are ravined by tributary channels. The Hudson River in America and the Congo in Africa open into submarine canyons five or six miles wide at their mouths. The outline of the continental slope has been studied more minutely on the eastern seaboard of America than anywhere else. There it has been found that between the deep and broad canyons are innumerable smaller chisellings, like the parallel rain gullies that can be seen on any soft railway embankment, and with the increase in the number of soundings around other continents it is becoming evident that these features of the slope are to be found everywhere. Though there has been much discussion about the formation of these canyons and of the smaller gullies, no completely satisfactory explanation has yet been found to account for them.

The term abyssal plain does not quite accurately describe the relief of the bottom of the deep sea beyond the continental slope. Again, as soundings increase in number, it is becoming clear that there are more irregularities in the floor of the ocean than was at first thought. There are shoals or banks and plateaux rising up 1,000 to 1,500 fathoms above the general level of the floor but still 2,000 fathoms below sea level. There are the swells, arc-shaped elongated plateaux like that running down

the middle of the Atlantic Ocean. There are the submerged pedestals that bear the oceanic islands and the deep troughs or trenches 1,000 to 3,000 fathoms below the general level of the ocean floor. On the whole it is becoming probable that the sea bottom is in reality as rugged in outline as the major features on dry land.

Our knowledge of the deposits which lie upon the floor of the deep ocean beyond the hundred fathom line is due mainly to Sir John Murray who examined the many hundreds of samples of the bottom brought back by H.M.S. *Challenger* from her voyage round the world in 1872–6. He made for the first time a map of the distribution of the various bottom deposits and much refined and detailed research since his day has not added anything essentially new to his discoveries.

The deep-sea deposits are either derived from the land and laid down in deep water near the coasts, or formed and laid down in deep water far from land. The former are known as terrigenous deposits and the latter as pelagic deposits. The terrigenous deposits consist of various kinds of mud, the very finest and most impalpable mud, with particles mostly less than 1/200th of a millimetre in diameter, that settle exceedingly slowly in conditions of almost complete stillness such as can only exist well outside the limit of wave action or strong currents. The most common kind of mud met with in the deeper water surrounding the coasts of the continents, and in the enclosed seas, is a bluish clay made of rock fragments and mineral particles, mostly quartz. At the surface of contact with the water above it the clay has a thin red or brown layer due to the presence of oxide of iron. It is really the reduction of this to ferrous sulphide and oxide that gives to the mud its blue colour.

A red mud covers large areas of the floor of the Atlantic Ocean near the coast of Brazil and off the coast of China (Plate IV). Here the giant rivers bring down a deposit with so much ferric oxide in it that it is not all reduced and the blue colour does not appear. Off high steep coasts free from large rivers, such as the Pacific and Atlantic coasts of North America, off Japan, off Australia and South Africa, where crystalline as opposed to sedimentary rocks are exposed, fine matter washed away from the land is less abundant. Rock fragments and mineral particles, therefore, remain longer exposed to the dissolving action of sea water and are not soon overlain by further sediments accumulating on top of them. They therefore become converted into a green silicate of potassium and iron known as glauconite. In the deeper waters off these coasts there are fine green sands made of angular glauconite particles, especially where, as off the Cape of Good Hope, cold and warm currents meet in the waters above. Muds of volcanic or coral origin will obviously be found around volcanic islands or near coral reefs.

The pelagic deposits, formed far from the land, either consist of oozes made of the skeletal remains of the animal or plant plankton, which have been steadily raining down upon the floor of the ocean almost since life first began in the sea, or they consist of a fine red clay. The oozes are made up of the remains either of calcareous or siliceous skeletons. Since calcium carbonate is more soluble than silica the calcareous oozes are found, on the average, covering the ocean floor at a lesser depth (1,000–2,000 fathoms) than the siliceous oozes (2,000–2,600 fathoms). The most widespread calcareous ooze covers large areas of the floors of all the ocean basins,

in all about 48 million square miles, from the South Pacific to the Arctic. It is particularly characteristic of the Atlantic Ocean (Plate IV). This is the globigerina ooze, made up largely of the shells of various Foraminifera, but especially those of the genus from which the deposit gets its name, *Globigerina.* It contains, however, the calcareous remains of many other creatures as well, some, like the coccoliths, from the surface waters but many from bottom-living forms, molluscs, worms and echinoderms. In tropical regions, where large-shelled Foraminifera occur, their remains can be seen in the ooze quite clearly with the naked eye, but globigerina ooze from polar waters looks simply like a very fine fawn or greyish powder. Another kind of calcareous ooze occurs in relatively small patches in the tropics and the sub-tropics, especially in the South Atlantic Ocean, covering an area of about half a million square miles. This is the pteropod ooze, made of the remains of sea-butterflies, which must occur in those areas in colossal numbers. The principal siliceous deposit is the diatom ooze made of the glass valves or frustules of diatoms. As one might expect it is characteristic of the ocean floor in those areas, under cold and temperate oceans, where the diatoms flourish in greatest abundance. It forms a band round the South Polar regions all over the floor of the Southern Ocean (Plate IV) from the approximate latitude of the antarctic convergence. There is also a band of diatom ooze across the North Pacific but, strangely enough, it is not found in the North Atlantic. A possible reason for this may be that the shallower depth of the temperate and polar North Atlantic causes the diatom remains to be masked by the globigerina. In other regions where the diatom ooze is abundant the

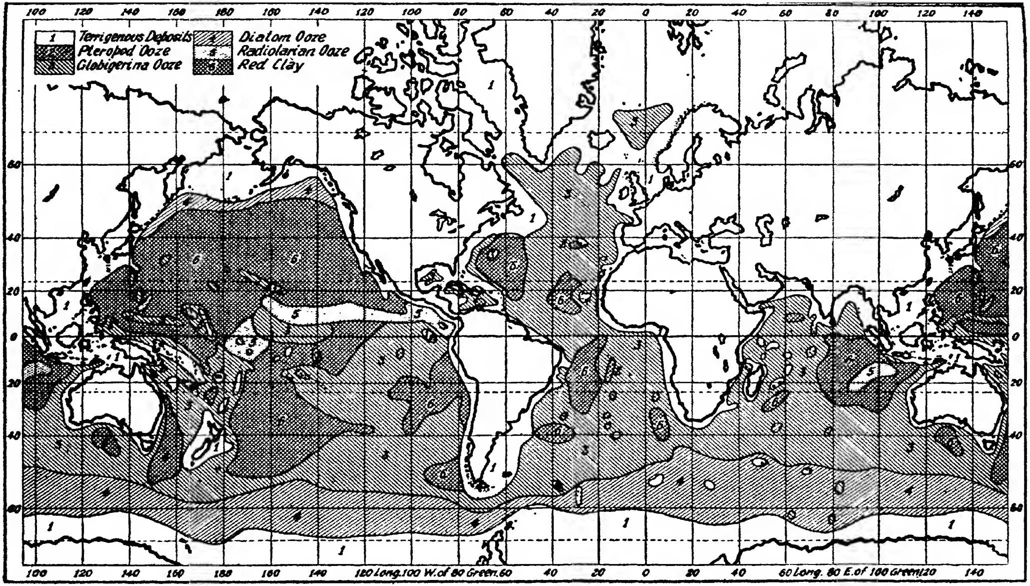

PLATE IV. Ocean Bottom Deposits.

calcareous oozes have been dissolved away. The diatom ooze covers an area, in all, of about ten million square miles. When dry it is a greyish white powder, but that which comes from areas near polar coasts may contain mineral fragments, carried and dropped by ice, which give the ooze a darker colour.

The remaining pelagic deposit, the red clay, is by far the most widespread of all the deposits on the ocean floor. It covers an area of about fifty million square miles. Vast areas of the Northern and Southern Pacific, eastern Indian and western Atlantic Oceans are floored with it (Plate IV). Its most common and constant constituent is volcanic pumice, chemically decomposed by the action of sea water. The average depth at which the red clay occurs (about 2,700 fathoms) is greater than the average depth at which any other deposits occur. It forms the ocean floor in the deep trenches under the deepest water in the world. At the greatest depths it contains no calcareous or siliceous constituents at all, but where it slopes up either to the globigerina or the diatom ooze it contains increasing quantities of them and finally merges into them. The pumice of which the clay is composed is made up of particles of all sizes from fragments the size of a man's head to minute grains that can only be seen with the highest powers of the microscope. They consist of 70 per cent. silica and alumina (aluminium oxide), the same proportion, in fact, as exists in igneous rocks. These volcanic remains, it seems, must have settled with almost inconceivable slowness in the water from airborne volcanic dust, perhaps with a small addition of ice borne fragments near the Poles. In addition to these there are found in the clay grains of iron and manganese peroxide and small metallic spheres

which are supposed to have formed the tails of meteorites or those showers of meteoric dust and meteoric showers through which our globe is constantly passing. These, then, are visitors from space outside our planet. Besides these there are also found the ear bones of whales and the teeth of sharks, sometimes, apparently of species now extinct. One must presume that these meteoric fragments and the insoluble remains of whales and sharks are equally widely distributed everywhere on the ocean floor among the other deposits, but their presence elsewhere is masked and overwhelmed by the other oozes or muds laid down along with them. Yet every sample of red clay contains some of them. How infinitely slowly, then, must the clay have been laid down to give so thick a deposit from so sparse a supply! The rates at which the blue terrigenous mud, the globigerina ooze and the clay have been laid down have, in fact, been calculated. For the blue mud it is about 1¾ cms. every 1,000 years. For the globigerina ooze it is about 1¼ cms. and for the red clay about ¾ cm. per thousand years. But even the slight disturbance which occurs in water at a depth of a thousand fathoms is enough to delay the settling rate very greatly. The longest core of the ocean bottom ever taken with the instrument known as the Piggot gun, which forces a tube into the deposit on the floor of the ocean by means of an explosion, was about three metres (10 feet) long. It must have taken at least a quarter of a million to three hundred thousand years to accumulate. Finally, a last kind of pelagic deposit remains to be mentioned, the radiolarian ooze. This is merely a red clay in which the siliceous skeletons of Radiolaria and the large disc shaped valves of the diatom *Coscinodiscus rex* become sufficiently abundant to form an appreciable

part of the deposit. It is found chiefly in the tropical Pacific Ocean and to a lesser extent in the Indian Ocean but not at all in the Atlantic (Plate IV).

It is not known how thick are the layers of soft oozes and muds which have thus slowly accumulated on the ocean floor. No bottom sampling instrument has ever yet penetrated to the rock base which, at some depth, must lie beneath them. This is the true floor of the ocean basin but we can only guess its character. We can draw conclusions about it from the rocks which form occasional islands rising sheer from the ocean bottom. Seismographic records also tell us something. The seismograph is an instrument which records the waves sent out through the substance of the earth's crust by earthquake shocks. The waves are of three different kinds, two kinds which radiate outwards from the shock centre through the whole extent of the earth's crust and a third kind which travels round the earth's circumference in the surface fifty miles or so of the crust. It was explained in the first chapter that the crust of the earth is composed of several layers of different density. A lighter granite layer builds up the continents, which rest and perhaps move upon a denser substratum. Earthquake shock waves travel faster through the parts of the earth's crust underlying the continents than they do through the parts underlying the oceans. We therefore infer that large parts, at any rate, of the oceans have a true floor made of the denser basaltic rock on which the continents rest. Yet the island peaks that rise up in the middle of the Atlantic Ocean, such as St. Helena and Ascension, are made of the lighter type of rock of which the continents are themselves built and it is for this reason thought that the median ridge of the Atlantic

Ocean may perhaps consist of the same kind of rock as the continents, with deeper basins of basalt on either side.

There is no depth of the ocean where there is not some life, however sparse and meagre it may be. On the continental slope and on the blue and red muds beyond it, down to the depth of the deepest dredging ever taken (3,125 fathoms), there lives a benthos population strangely adapted for living on this impalpable substratum. Even in bottom cores brought up by sounding tubes from greater depths than this the remains have been found of Foraminifera and sponges which probably live in the lower reaches of the abyss. The deepest net hauls yet made, in about 1,000 to 1,500 fathoms, have revealed a strange population of crustacea and of fishes astonishingly and, to our minds, hideously distorted for life in their cold, dark, silent world.

It is interesting to speculate upon the kind of world which animals inhabit at these great depths. In the first place the hydrostatic pressure is enormous. At sea level the pressure of the atmosphere upon our bodies measures about 15 lbs. to the square inch, but we do not perceive it because it bears equally upon us both within and without the cavities and tissues of the body. If there were a cavity within our body containing a vacuum or air at a lower pressure than 15 lbs. to the square inch it would cave in, as indeed our chest tends to do when we reduce the pressure in it by exhaling. Below the surface of the sea the pressure increases one atmosphere, that is 15 lbs. per square inch, for every 33 feet of descent. At a depth of 3,000 fathoms, then, the pressure will be about 3 tons 15 cwt. per square inch. However, since water is almost incompressible, and since this pressure bears in all directions both inside and outside the cavities and

living tissues of the body, even the most fragile and delicate creatures are unaffected. In just the same way a metal box, sunk to the bottom of the sea, keeps its shape even at the greatest depths if its sides are perforated so that the pressure of the water can bear both inside and out. If it has riveted seams, but no holes, the seams burst and the water forces its way in, and if it has neither seams nor holes it is squashed flat long before it reaches the bottom. Sunken ships, therefore, remain unchanged in shape in their last resting place except for any tanks or compartments into which the water cannot easily penetrate. They will be burst inwards.

Pressure, then, does not much affect life in the great deeps. The temperature just above the ocean floor is around freezing point and varies between 2° below freezing point and 10° Fahrenheit above it, but at the surface the richest seas in the world, where life is most prolific, have similar temperatures. The oxygen necessary for respiration is present in sufficient quantities at even the greatest depths because of the sinking of cold water at the Poles whence it creeps along the bottom towards the tropics. Except, therefore, in isolated situations such as the deepest Norwegian fjords and in the Black Sea, the water at the bottom of the oceans is never stagnant. The principal factor which influences life at great depths is the complete or almost complete lack of light. It is an adverse factor. In clear water plant life can carry on its indispensable photosynthesis down to a depth of about 250 feet and in water which is at all turbid the process ceases at a very much smaller depth. Below a depth, then, of about 50 fathoms at the most there is no plant life which could form the food of a large herbivorous population. But in the

shallower deep-sea areas dead plant and animal skeletons raining down still contain some organic remains when they reach the bottom and it is on this organic debris that the deep-sea benthos feeds. In the greater depths the organic remains have been dissolved out on the journey down and only the empty skeletons reach the bottom. It follows, therefore, that the inhabitants of the deeper parts of the abyss are carnivorous. They largely eat each other. But in that vast dark space the inhabitants do not often meet and, therefore, in order to make doubly sure that any chance encounter between shall make a meal for one or the other, abyssal fishes have relatively gigantic cavernous mouths and formidable teeth like scimitars (Fig. 11, *Macropharynx* and *Linophryne*). For the same reason, because chance encounters must be few and those between opposite sexes of the same species even fewer, the females of many of these strange fishes carry their males about on their bodies (*Edriolychnus*), very much reduced and even inseparably fused with their own tissues. Nevertheless, in spite of the lack or poverty of light, all the deep sea fishes have eyes, very often greatly enlarged and borne on the end of upwardly directed stalks (*Argyropelecus*) so that they are probably telescopic. We must assume, therefore, that they use them, for if they did not they would become blind. But in order that eyes may be able to see there must be light of some sort. The human eye can just perceive light which is one thousand millionth of the strength of bright daylight. In clear ocean water light of this very low intensity prevails at a depth of about 350 fathoms and photographic plates exposed for two hours showed traces of the action of light down to 500 fathoms but between 800 and 900 fathoms plates show no signs of exposure

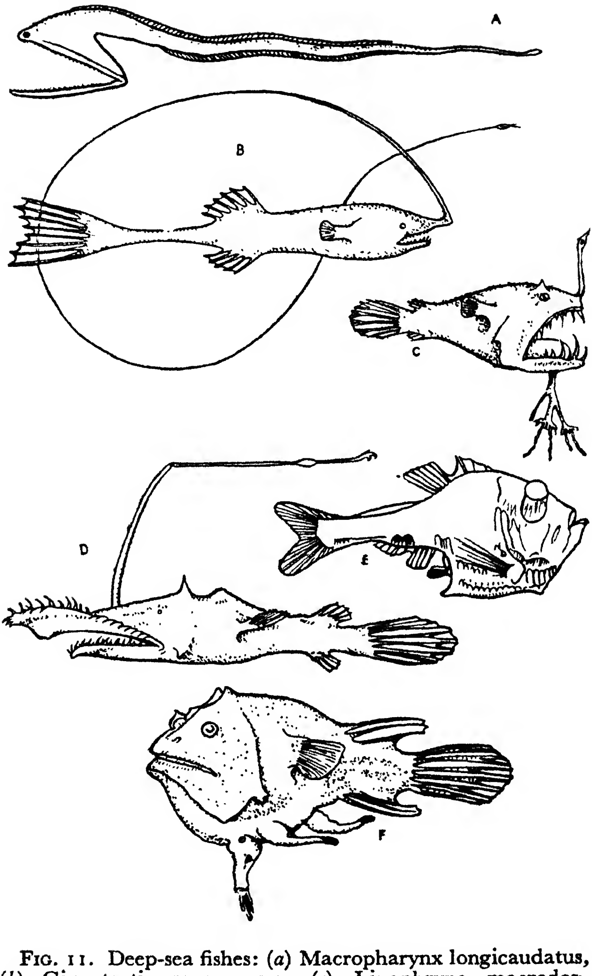

FIG. 11. Deep-sea fishes: (*a*) Macropharynx longicaudatus, (*b*) Gigantactis macronema, (*c*) Linophryne macrodon, (*d*) Lasiognathus saccostoma, (*e*) Argyropelecus hemigymnos, (*f*) Edriolychnus schmidti.

after two hours. Yet even in this complete darkness fish still have eyes and the only light which they can perceive at such depths must be that which they themselves emit, for a very great many of them have light producing organs. These are borne on the ends of stalks or protuberances or along the sides of the body. The pale glow these organs produce probably acts as a lure to other fish and in some of these small nightmares from the deep the light organ is borne on a long curved filament which projects like a sort of fishing line from the top of the head (*Lasiognathus*, *Gigantactis*) in a way that strongly suggests its function.

Animals that live on the bottom beyond the hundred fathom line are mostly specially adapted for living in soft impalpable mud. Many of them have long stalks which keep them clear of the sea floor and there is a sea-squirt (*Culeolus*) which lives in the abyss floating clear of the mud like a balloon on the end of a thread two or three feet long. Some of the clay bottoms are covered with forests of sea-lilies (Crinoidea) which are echinoderms, related to the feather stars of the shallow water zone. Their five-rayed symmetrical body is borne aloft on the end of a long stalk anchored in the mud by means of a holdfast. The sea-pens (Pennatulacea), which also grow thickly in places, are colonial polyps and resemble the false corals except that they have an internal skeleton of horn instead of a calcareous external one. The polyps live on a branching plume with lateral growths like a wing feather. At its lower or quill end the plume has a smooth tapered shaft which sticks into the mud. Many of the crustacea which crawl over the mud have enormously long legs (*Munnopsis* and *Nematocarcinus*) which prevent them from sinking down into it. Some of the

urchins (Cidaroidea) that live buried in it have immensely thickened spines which serve the same purpose. But perhaps the most striking thing that one notices about animals that live on the bottom in deep water is their delicacy and fragility, evidence of the almost complete stillness in which they live. It is very seldom that they come up undamaged in the dredge. The thickened, apparently heavy but really very light, spines of the urchins drop off at the least touch. Their skeletons are made of uncompleted plates not joined along their edges. The arms of sea-lilies snap off very easily and the great glass sponges, many of them of lovely and classic shapes, stand on the mud upon rounded bases giving no anchorage at all. The sea-pens stand upright with only a smooth shaft to hold them in place.

Nevertheless, very little is known about the inhabitants of the cold, dark and almost motionless deeps. There may be many kinds of animals living there which have never yet been taken with net or dredge. We know, at any rate, that there are deep-sea squids of gigantic size, probably too swift moving for any net to catch, which are only known from the remains of them found in the stomachs of Sperm whales. Fishing with large nets in very deep water is a difficult and expensive task. Nets behave under water in the most unexpected manner and the most carefully designed apparatus, which seems faultless in theory and works perfectly in shallow water, may fail altogether in the open ocean on the end of several thousand fathoms of steel warp. And even if the apparatus does act correctly, long hours of patient waiting and watching may bring no reward, for as often as not the net comes up almost empty.

CHAPTER VIII

SEA FISHERIES

Demersal fish—Pelagic fish—Trawling—Lining—Drift netting—Life history of the cod—Flat fishes—The plaice—Effect of trawling—The herring fishery—The stock of fish on the grounds—Density of the stock—Decline of the home fishing grounds—Catch of young fish—Size limitation—Mesh regulation—International agreement—Fishery research—Transplantation of fish.

THE GREAT fisheries, which provide food for the millions of the world's continents, are situated entirely upon the continental shelf or upon the edge where the shelf steepens into the slope down to the abyssal plain. Here live the fish caught with the line and the trawl, such as the cod, the haddock and the plaice, feeding on the rich benthos population of the shallow water zone. Here, too, the fish taken with the drift net, such as the herring, feed on the abundant neritic plankton.

Off the north-west coast of Europe the continental shelf extends outwards round the British Isles forming a shallow platform from northern Norway to the coast of Portugal. The North Sea and the Bay of Biscay lie within its boundaries. Here, and on the shelf around Iceland, around Bear Island far to the northward and off the Arctic coast of Russia, is the largest, the most intensive and the richest fishery in the world, in which all the nations of the northern seaboard of Europe take part. Second in importance is that of the eastern seaboard of America, which includes the famous cod banks of Newfoundland. The Japanese fishery possibly directly

employs more men than either the European or the American but, since it is carried on almost entirely by individual fishermen with small boats, it is hardly comparable to the heavily capitalized and mechanized fishing industries of the western countries.

Our food fishes are of many kinds but broadly we may distinguish those which spend their adult lives on the bottom, feeding on the benthos, from those which spend their lives swimming in shoals near the surface, feeding on the plankton. The bottom-living or demersal fish are those which are taken with the trawl or the line. Their eggs are lighter than sea water and, after they have been shed, they rise to the surface to become the fry which, as young fish, eventually sink to the bottom. By far the greater number of our food fishes are demersal and among them again we may distinguish the round and the flat fishes. The terms explain themselves. The round fish have the orthodox streamlined shape, like the cod and the haddock, and the flat fish are those, like the plaice and the sole, which, as an adaptation to their habit of lying on the bottom, are flattened laterally into a leaf-like shape. The upper side is coloured and the lower side is white while both eyes are on the upper side of the body. In the plaice and the sole, when the young fish settles down on the bottom, the left eye actively migrates round to the right side of the head and the fish lies on its left side. The turbot and the brill, however, lie on the right side and it is the right eye which moves round to the left. Other flat fish are the skates and rays which are quite different. They are related to the sharks and dogfish and are flattened from above downwards so that their eyes are not displaced.

The fish which swim in shoals near the surface, feeding

on the plankton or other small fishes, are known as pelagic fish. The most important in our waters are the herring, the most abundant of all our food fishes, and the mackerel. Some have eggs which are heavier than sea water. The herring alone of all our commercial fish actually lays its eggs on the bottom, in crevices among stones or on seaweed. The mackerel, on the other hand, sheds its eggs near the surface where they slowly sink and come to rest on the bottom.

There are very many ways of catching fish practised by fishermen all over the world. Our commercial bottom-living fish are taken principally with the trawl and the line, and the herring is taken with the drift net. The trawl is, in essence, simply a bag of netting (Fig. 12*a*) which is hauled along to the bottom and which scoops up all the fish which lie in its path. In the nineteenth century, when all the trawlers were sailing ships, the beam trawl was used. In this the mouth of the bag was kept open by a wooden beam supported some feet above the bottom on metal runners called trawl heads. But towards the end of the century, when steam began to replace sail, the modern otter trawl was introduced. In this type of trawl the mouth of the net is attached at each side to a weighted rectangular wooden board or door. The two boards are hauled through the water by the trawling wires and are set at an oblique angle so that they diverge from one another, pulling agape the mouth of the net. The lower margin of the mouth, reinforced by a stout rope called the foot rope, is considerably longer than the upper margin which is reinforced by another stout rope called the head rope. The foot rope, therefore, trails over the bottom as a backwardly directed U with a roof of netting above it and the fish are swept

back into the conical cod end of the net. This type of trawl has many advantages compared with the older type. The beam trawl became too cumbersome and heavy at greater lengths than about fifty feet, but the otter trawl is scarcely limited by size at all and almost any manageable length of foot and head rope can be used. Modern otter trawls have a mouth about a hundred feet in width. Of recent years several refinements have been introduced to make the otter trawl even more effective. Wooden or metal rollers, the bobbins, are threaded along the foot rope so as to enable it to run over rough bottoms of rock or stones. In 1923 a new pattern began to be used, known as the Vigneron-Dahl trawl, in which the sides of the mouth of the net are separated from the boards or doors by long wire bridles. It was found that about 25 per cent. more fish were swept into the net with this modification than with the older type in which the head and foot ropes were attached direct to the doors. The strain of such an apparatus travelling over the bottom is, of course, very great and, as trawls have become larger and heavier with modern improvements, the ships which operate them have grown in size. In 1906 the average size of English trawlers was about 170 gross tons, but in 1937 it was about 270 gross tons, though this increase in size is also largely due to the shift of the trawling grounds from the North Sea to Iceland and the Arctic, involving fishing trips of three weeks to a month instead of only a few days. A trawler is easy to spot because of the two hoop-shaped gallows on each side, one forward and one aft, which carry the trawling wires, and because of the powerful winches which she carries on the foredeck for hauling the steel warps.

The vast majority of the fish we see at the fishmonger's

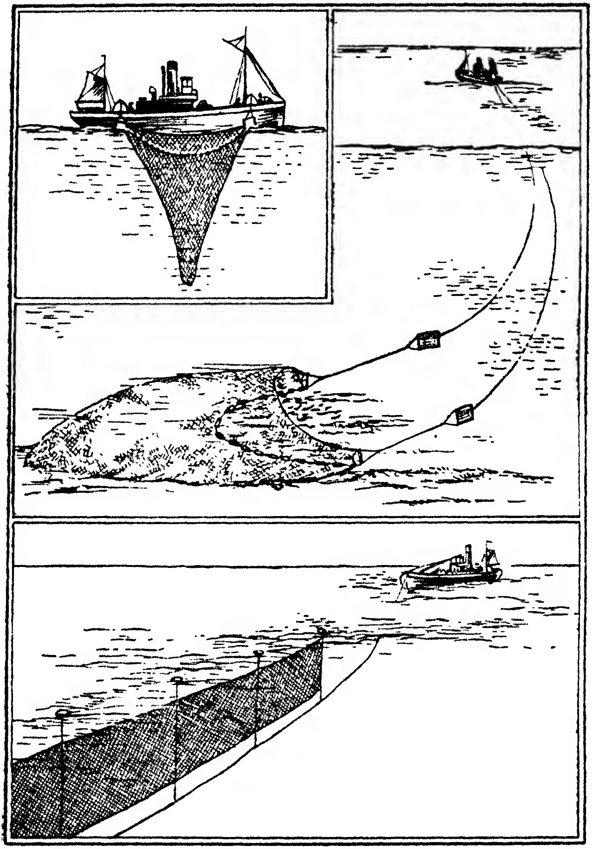

Fig. 12. *Upper*: Otter trawl, with Vigneron-Dahl extensions, sweeping over the bottom. (Inset: Trawl hauled close to the trawling gallows.) *Lower*: Herring drifter with drift nets.

is taken with the otter trawl and comes in modern trawlers, packed in ice, from as far afield as the Iceland banks, Spitzbergen and Novaya Zemlaya. Small quantities of fish, however, cod, haddock, ling and halibut, are still caught with lines. Inshore lines for cod and haddock are laid at night across the tide, anchored and marked with a buoy at each end. Every two yards along the line is fixed a short length or snood which carries a baited hook. On the continental edge around Newfoundland and on the edges of the Iceland banks a certain amount of deep lining is still done for cod, ling and halibut with long lines carrying thousands of hooks laid along the bottom.

The drift nets, which are set for herring all round our coasts, work on quite a different principle from the trawl. The net is simply a curtain which hangs in the water (Fig. 12*b*). The diamond-shaped meshes of the net are of such a size that the fish become entangled in them, firmly held behind the gill covers. Each net is about 34 yards long and about 14 yards deep and the nets are strung together so as to form a continuous wall of netting, possibly several miles long, called a fleet. There may be as many as 135 nets in a fleet. The upper edge of the fleet is buoyed with floats while the lower edge is weighted so as to keep the net hanging vertically. The nets are shot at night from small ships about half the size of a trawler, often lying so close together that it is astonishing that the fleets of nets do not foul one another more often than they do. At night the plankton rises to the surface and the herring rise also to feed. Unable to see the walls of net in the dark the shoals of fish charge into them and become stuck in the meshes, unable to move forwards or backwards. When the nets are hauled

in at daylight a silver cataract of fish is shaken out.

The round fishes taken with the trawl on the continental shelf from the Arctic to Biscay are of many kinds. Around Iceland and in the waters to the north they are mostly cod, coal fish and haddock, usually in that order. All these are members of the cod family. The cod (*Gadus morrhua*) is a fine olive green or brown fish with dark spots and a sensitive barbel on the chin. The coal fish or saithe (*G. virens*) is almost black in colour and has no barbel on the chin. We meet the coalie more often than we know for much of the cheaper sorts of fish sold in restaurants and fried fish shops, sometimes as cod and sometimes simply as fish, is coalie—rather coarser and less delicately flavoured than cod. The haddock (*G. aeglefinus*) has a more rounded shape and is smaller than either the cod or the coal fish. It is easily spotted by the black St. Peter's thumbmark on each side above the pectoral fin where St. Peter is supposed to have pulled the fish out of the lake Genessaret—regardless of the fact that the haddock can never have lived there. Around Iceland and farther north the cod and the coal fish are more abundant than the haddock but southward towards British waters the haddock takes first place. Farther south still in the Bay of Biscay the haddock, in turn, gives place to the largest of the cod family, the hake (*Merluccius merluccius*). Another of the cod family, the whiting (*Gadus merlangus*) is taken in the trawl anywhere from the Mediterranean to Bear Island and is spotted by its silvery colour and the black smudge at the root of the pectoral fin.

Besides these prime fish the trawl takes numerous others of inferior quality, such as the catfish, the gurnard and the dogfish, but these we must neglect and consider

one round fish only—the cod, the most important of all the food fishes of European seas. In 1938 nearly 350,000 tons were landed in Great Britain alone. We may take its life history as typical of all the demersal round fishes for the others differ from it only in details such as the time and depth of spawning, the type of food—which affects the kind of bottom they frequent, and the rate of growth.

The cod is taken on the trawling banks all the year round in depths between 10 and 100 fathoms but mostly in less than 40 fathoms. The best catches, however, are taken in the spring (January to March) when the mature fish gather on their spawning grounds. These are quite well defined and well known. In general the depth of the water where the cod spawn is between 20 and 30 fathoms. The spawning grounds in the North Sea are situated wherever the water has about these depths, chiefly the northern and central areas. Off Iceland they are to the south and south-west of the island. Off the coast of Norway there is a great spawning ground around the Lofoten Islands where there is a heavy fishery in the spring. The cod start moving to their spawning grounds in the early winter. In the North Sea they come from the shallow water round the Norwegian and British coasts where they have been feeding during the summer. Off Iceland they come from the northern and eastern banks and to the Lofotens they come from the banks around Bear Island. The cod is exceedingly fecund for a single female may shed in the spawning season between four and six million eggs. But only two of these need survive in order to continue the race. The eggs are simple transparent spheres one-twentieth of an inch in diameter. After they have been shed and fertilized by the sperm spilt into the water at

the same time, they rise to the surface and continue their development floating about at the mercy of currents and of chance and of innumerable enemies. The young fish develops upon the egg as an embryo with relatively enormous eyes and a slender body curled on the surface of the yolk-laden sphere. It feeds on the yolk of the egg for the first few days, the egg hanging below the growing fish like a sac, slowly diminishing until all the contents have been used up. After a few days, however, this supply of food is exhausted but by that time the little fish has formed a mouth and a gut and begins to feed for itself on microplankton. When they are about an inch long the little plankton feeding larvae adopt a strange method of protecting themselves from their enemies, for they seek out the great jelly fish, the sluthers (*Cyanea*), which in the spring abound in the creeks and shallow waters of the northern coasts. Some of these reach a gigantic size, six or seven feet across. Safe in these voluminous tents the little fish, with the fry of the haddock and the whiting as well, continue their growth protected by the stinging tentacles of the jelly fish. On a fine day, when the water is clear, the great bells can be seen pulsing along like disembodied hearts, trailing their long tentacles, each surrounded by a cloud of little fish which dart back under cover of the bell at the least disturbance. It is a mystery how the fish themselves avoid falling victims of the stinging tentacles. They live in their floating home for a week or two and then settle on the bottom where they remain for the rest of their lives. Meanwhile they have drifted far and wide away from the banks where they were spawned, into the shallows and into bays and inlets around the coast. In the North Sea young cod are particularly numerous at the tail of the Dogger Bank and

in the Moray Firth during the summer. The young cod are found mostly in shallow inshore waters in the early years of their lives and move out to deeper water as they grow towards maturity. The cod is a predaceous and catholic feeder. It prefers a hard stony ground and feeds at first on small crustacea, worms and molluscs. Later it takes to eating fish—herring, sprat, young haddock and the young of its own kind. At the end of their first year cod are seven or eight inches long in the North Sea but in northern colder waters growth is slower and the young cod only achieve a length of about three inches by the end of their first year. In the fourth year they are mature and ready to spawn, by which time they may be two or three feet long. Up to that length they are known to the fishermen as codling and often spoken of as though they were, in fact, a different kind of fish altogether. The cod are in the best condition at an age of five or six years. At ten years old they may reach a length of five feet or more and, if mankind and their enemies spare them, they may live to be twenty years old but they are by that time very ancient fish. The same age limit, indeed, seems to hold for all our principal food fishes, the haddock, the herring and the plaice as well as the cod.

Experiments on the marking of cod with metal discs have shown that after the beginning of their adult life the fish make limited but regular migrations, to the spawning grounds in the spring and out to deeper water down to 40 fathoms for feeding in the summer. But the populations of various areas seem to be more or less self-contained and there seems to be no interchange between the cod of, say, the North Sea and those of Iceland, or between those of Iceland and those of the Norwegian coast.

After the cod the haddock is the most important of our food fishes. Nearly 150,000 tons were landed in Great Britain in 1938 and together the catches of cod and haddock made up more than half the total demersal fish landed in that year. It is a slightly more southern fish than the cod and is not found so abundantly in the far north nor on the western side of the Atlantic. The largest catches come from the northern North Sea, the Faeroes and Iceland. Southward towards the Bay of Biscay the hake takes its place. It swims about in shoals consisting of fish all of the same size and, unlike the cod, chooses a soft sandy bottom, for it is not a predaceous feeder and its diet consists mainly of molluscs, worms and small crustacea. It spawns rather later than the cod (March to April) and always in deeper water, in about 40 to 60 fathoms. It is, in fact, altogether a deep-water fish and the young are never found inshore in shallow water in the early stages of their lives. After it has attained its adult form it remains out in the open sea and, for the first year of its life, does not seek the bottom. It moves to the spawning grounds and spawns for the first time in its third or fourth year.

The life histories of the flat fishes are much the same, in general plan, as the above except for the extraordinary transformation which takes place when the young fish settles on the bottom and the eye on the underside travels round to the upper side of the head.

Of all the flat fishes the plaice (*Pleuronectes platessa*) is by far the most important and in 1938 about 26,500 tons were landed in Great Britain alone. It may be recognized easily by the round red spots like pennies on its upper surface. The common plaice ranges over the whole European continental shelf from the Barentz Sea

to Biscay but, though it is caught in larger quantities than any other flat fish, yet the sole is the most highly priced of all our food fishes, except perhaps the turbot. There are several types of sole that reach our markets but the common sole (*Solea vulgaris*) is the most important one. It can be recognized easily enough by its long slender shape, its speckled sandy colour and the fact that the head juts forward in front of the eyes. The sole is a nocturnal fish and gropes its way about over the bottom by means of tufts of sensory whiskers on the under blind side of its head. It is a southern fish and is not taken either off the coast of Scotland or of Norway.

The flat fish start life as perfectly symmetrical larvae like those of the round fish. They spawn in the spring on definite and well established spawning grounds. In the North Sea there are three spawning grounds for plaice, off Flamborough Head, east of the Dogger Bank and, the most important, off the Flemish coast. The egg hatches and develops at the surface, the embryo feeding at first on the yolk of the egg. But at a certain stage, after the thirtieth day, the left eye begins to move forwards and upwards and by the fortieth day is on top of the head. Meanwhile the young fish has taken to swimming on its side, right side up. By the forty-fifth day the left eye has arrived at its final position above and in front of the right one. A gradual change of diet accompanies this change of posture. At first the young fish eats the larvae of crustacea but when it begins to swim on its side it takes to eating copepods as well. When, at an age of six or seven weeks, it settles down on the bottom as a flat fish lying on its left side, the food changes to various worms and small bottom-living crustacea (Mysids). Later the adult fish takes to feeding on cockles and mussels and,

on the Dogger Bank, on a mollusc (*Spisula subtruncata*) like a small cockle, which it finds there in enormous numbers. The female plaice is mature and ready to spawn in its fifth year, by which time it has grown to a length of about a foot or fifteen inches, but its actual size at the first spawning varies in different waters. Marking experiments have shown that the plaice is a sedentary fish on the whole and tends to keep to restricted areas, though it does make regular short migrations, moving to its spawning grounds in the spring and out to cooler, deeper water offshore in the summer.

The sole has a similar life history to the plaice but spawns on more localized grounds in deeper water, about twenty fathoms.

Among the demersal fish, of which the cod and plaice have been singled out as examples, the modern mechanized methods of fishing wreak fearful havoc. For the stocks of fish are far from inexhaustible. They live in self-contained areas of limited extent and the movements of the fish populations are restricted. Each sweep of the trawl gathers up not only mature and nearly mature fish of marketable size but also thousands of young ones too small to be of use. These are all swept back into the sea, or were until the introduction of the standard mesh for trawls did something to reduce their capture, where they are of use only as food for kittiwakes and black-backed gulls. Many other small fish escape through the meshes of the cod end but it is unlikely that many of them survive such rough handling. Further the trawl scoops up and injures many thousands of molluscs, worms and small crustacea on which the fish feed. The heavy bobbins of the foot-rope crush and trample down the sea-fans, the dead men's fingers and the corallines among which these

creatures live. Each sweep of the trawl, indeed, scorches the earth along the bottom of the sea, leaving a trail of ruin and destruction behind it. The result has been the steady dwindling of the stocks of fish on our home grounds which has been going on for a quarter of a century. Only by going farther and farther afield from the central North Sea to the northern North Sea and the Faeroes, then to Iceland and Bear Island and now to Spitzbergen and the Arctic coast of Russia have our trawlers been able to keep up the supplies of demersal fish, to keep the markets full and themselves in a hard won living. In 1929 a most astonishing and, for our trawlermen, Heaven-sent change took place in far northern waters. There was a general warming up of the surface waters of the whole North Atlantic Ocean. The result was an increase in the stocks of cod in the far north and the great cod fisheries around Bear Island really came into existence at that time. Similar changes have taken place before in the North Atlantic and have been only temporary, lasting for a few years, before the waters returned to their former temperature. No one can tell how long the present conditions will last.

With the pelagic fish, however, the situation is at present quite otherwise. There seem to be such vast stocks of herring that there is no danger of any shortage arising from any man-made cause—at least in the near future. The herring is, in fact, the most abundant of our food fishes. At the height of the east coast herring season a single drifter may take 300,000 herring in one good night's fishing. At the outbreak of war 250 drifters were working out of Yarmouth and Lowestoft alone so that 75,000,000 herring might be landed from these two ports in one night. Yet sudden disconcerting shortages

do occur, such as that which almost completely put an end to the Plymouth fishery in the early thirties. But these, whatever their cause, have nothing to do with the activities of man.

In the year before the war nearly 270,000 tons of herring were landed in Great Britain. Luckily the drift net fishery does not carry within it the germs of its own dissolution as the trawl fishery does. It does not harm the food of the fish for the herring is a plankton feeder. It does not harm the eggs for they are laid on the bottom —on ground so hard that even a modern trawl with bobbins rides over them. Further the meshes of the net are so arranged that all fish less than four years old escape through them undamaged and live to spawn again.

The herring drift net fishery starts in the Hebrides in May when vast shoals appear off Stornoway. In June it spreads to the Orkneys and Shetlands. In July the towns along the Scottish coast begin, Buckie, Peterhead, Frazerburgh, Aberdeen. But after a few weeks the fishery begins to slacken in these northern ports and by July and August that at Scarborough and Grimsby is in full swing. In October, Yarmouth and Lowestoft send out their fleets of little ships. In January, until about 1933, there was a winter herring fishery at Plymouth, but, for reasons already explained, this has now all but died out. There are huge herring fisheries along the Norwegian coast, in the Baltic, on the west coast of Ireland, in the Clyde and down the east coast of Canada and the United States. As the fishing moves down our east coast the troops of Scottish fisher girls follow it to gut the fish, salt and pack them. Very early on autumn mornings the streets of staid English towns echo with their loud

laughter and alien voices and with the tramp of their feet going to work.

The southward movement of the herring fishery gave rise to the idea that the fish congregate in the Arctic and, in the spring, move southwards as a vast army sweeping down the North Sea and the west coast into the Channel. But it is now known that this is not so. The herring lives offshore in deep water all the year round and at certain times collects together in shoals which move inshore to spawn. The times of the fishery all down the coast coincide with this inshore movement which is probably dependent, among other things, on the temperature of the water. However, the life history of the herring is still comparatively little known and it is not certain just what happens when the herring move inshore nor why they do it. When the drifters pay out their nets across the tide they may wait all night and catch only a few fish, although they know by all the signs that fishermen learn to read—the gathering birds, the leaping porpoises—that herring are about. Then suddenly something inexplicable takes place, known as the 'swim'. Over hundreds, even thousands, of square miles the fish, possessed perhaps by some sudden nameless ecstasy or excitement, rush in a silver torrent against the nets and are entangled there. The swim usually takes place at certain times, at sunrise, at sunset and at low-water slack. What causes it no one knows though fishermen have many theories. It has, at any rate, some connexion with spawning and may have something to do with feeding, since the herring of some of the northern fisheries are feeding, while at most of the southern ones it is taking no food and all the fish have empty stomachs. The spawning takes place in quite shallow water and there seem to be two spawning

times, spring and autumn. It is not known, however, whether the same fish spawn twice a year or whether there are separate spring and autumn spawning herring. Those who hold the latter view say that there are two races physically distinguishable from one another by the numbers of their vertebrae, their bodily proportions and the numbers of scales on the belly. One race spawns in the spring and the other in the autumn. Others hold that eighteen months elapse between one spawning of each fish and the next and that those which spawn in the spring do not do so again until the autumn of the following year. The first spawning takes place when the fish is five years old by which time it is just large enough to be caught in the drift net. It feeds during its adult life on copepods (very often dense shoals of *Calanus finmarchicus*), on a euphausiid *Meganyctiphanes norvegica* and on arrow worms. All these small creatures it filters out of the water by means of comb-like processes on its gills called gill rakers.

In the years immediately before the war the British fishing industry was the greatest of all the European nations except Russia. In 1938 the total value of the British catch was a little over £16,000,000 and, by weight, amounted to slightly over a million tons. Until the end of the nineteenth century fishing was carried on around our coasts by sailing trawlers and drifters but in the eighties steam began more and more to replace sail. Fishing gear became more ruthless and efficient especially as the otter trawl began to replace the older beam trawl. As a result the stocks of fish close inshore began to decline and the trawlermen found that they had to make longer and longer journeys to fill their holds. The close of the century saw fishing moving ever farther outwards

to new grounds. In 1868 a Royal Commission had abolished all controls over fishing but in 1883 the fishing trade, alarmed at the depletion of the inshore waters, summoned the International Fisheries Conference, which met under the chairmanship of Thomas Henry Huxley. In his opening address, however, Huxley expressed the opinion that 'nothing we do seriously affects the number of fish'. Nevertheless the numbers of fish continued to be most seriously affected during the closing years of the old century and the opening of the new.

It hardly needs to be said that fishermen are among the finest men these islands breed. The constant battle with the sea and with uncertain fortune, which is his life, gives a staunchness, a simplicity and rough kindness to the fisherman which all who have worked or lived with him well know. Twice in a single lifetime his country has called upon him and not in vain. It would be all the more tragic, therefore, if a melancholy decline were to overtake his industry.

When steam replaced sail at the beginning of this century an enormous expansion of the British fishing industry took place, but since the war of 1914–18 there has been a decline. In 1883 there were 225 first-class steam fishing vessels (15 tons gross or more) and 8,283 sail. In 1913 there were 3,296 first-class steam and 3,130 sailing vessels. In 1937 there were 3,350 first-class steam and motor vessels and only 50 first-class sail. In 1913 there were 100,000 men employed in fishing in the British Isles but in 1937 there were only 50,000.

At the end of the nineteenth century it was the custom to transfer the catch at sea to fast sailing cutters for transport to the market ports. This arduous system,

known as fleeting, often meant danger and even loss of life for, since there was no refrigeration in those days, it was not often that the weather was allowed to interfere with the transfer. But nowadays the modern trawlers, equipped with refrigerating plant, bring their catches into port and express trains with refrigerated vans take them all over the country. The total British yield, for demersal fish only, rose from about $3\frac{2}{3}$ million cwt. in 1886 to nearly 9 million in 1907. There was a great drop in the yield during the war years, 1914–18, but it quickly recovered after the war and remained around its pre-war level until the early thirties when new high levels were reached. In 1937 between 13 and 14 million cwt. were landed. However, the real test of what is happening to a fishery is not the total yield so much as the average catch for each day that every vessel is away from port. This is known as the density of the stock. We find that as the resources available for attack on the fishery—that is, the number and size of the boats, the efficiency of gear and so on—increase, the total yield at first increases too. But the first sign of depletion of the stock of fish is shown by a fall in the density, though the total yield may for the time being go on increasing. Sooner or later the total yield itself beings to fall. The figures for the density of our stocks of demersal fish at first sight seem to indicate that all is well. In the years before the war of 1914–18 the figure was fairly steady at about 23 cwt. per day's absence. During the years of the first World War the fish on the North Sea grounds rested and recovered. Afterwards there was a short boom because the grounds had replenished themselves. They were, in fact, overcrowded and on that account the fish were of small size. But the uncontrolled scramble to reap this harvest after

the war soon exhausted the stock and the density fell disastrously, from 36 cwt. in 1919 to 20 cwt. in 1923. After that it rose fairly steadily to about 38 cwt. in 1937. Nevertheless that rise was only achieved by extending fishing farther and farther afield, to Iceland, to Bear Island and to the White Sea. Until the outbreak of war in 1939, then, both the total yield and the density of the stock for the northern fishery as a whole were on the upgrade, while the figures for the chief demersal fish separately on the home and Iceland grounds show that both the density and total yield have been falling steadily since the boom after the first World War. In Iceland the cod formed an exception for both the yield and the density rose steadily until 1932 when they began to fall off. It was in the early thirties that the Iceland grounds first began to be intensively fished. On these home and Iceland grounds the decline has taken place in spite of, and indeed because of, the enormous increase in fishing power since the first World War. It is not necessary to quote the figures here but only to say that they show that the total figures, both yield and density, of our demersal fishery are nowadays entirely dependent upon the far northern and Arctic stocks of fish, so greatly replenished by the increase of cod which took place after the temperature change in the surface waters of the North Atlantic in 1929.

Another sign of overfishing in a stock of fish is an increase in the numbers of small young fish and a decrease in the numbers of older large fish in the catches. This too has been taking place on the home fishing grounds to a dangerous extent. The plaice become mature at about 39–40 cms. (about 16 inches) in the North Sea and the Barentz Sea. As long ago as 1907 it was

found that of over 2,000 fish measured in northern waters nearly all were over 40 cms. long and mostly mature while of about 900 measured in the North Sea nearly all the fish were under this length and immature. In the North Sea, therefore, the catches even then consisted almost entirely of fish which ought to have been allowed a chance to spawn and replenish the stock but were never given time to do so before being swept up in the trawl to the detriment of the next year's brood of young.

However, this state of affairs, the steady depletion of the home fishing grounds, had been foreseen. In 1902 the International Council for the Exploration of the Sea was established in Copenhagen. It was realized that fishery questions must be dealt with by international agreement and the object of the Council was to carry out scientific investigations into the stocks of fish and make recommendations for the control of the industry. There were several ways in which this control might be exercised if the nations could agree to act together. They all turned upon this fact, which we have just noticed, that in each kind of fish, but particularly in the plaice, far too many small immature fish were being taken by the trawl, a dead loss to next year's fishing. It was at first suggested that it might be possible to close certain areas of sea to fishing at certain times of the year when the young fish were known to congregate there. However, there proved to be practical and political objections to this idea and the fishing industry was opposed to it so that the suggestion was dropped. Another suggestion arose from the fact that if young plaice are transferred from a densely crowded area to a less crowded one, where food is more abundant, their growth is speeded up so that they reach a much larger size in a shorter time. Several

small scale experiments on these lines had been successful with plaice and it was recommended that much larger transplantations should be undertaken. Thousands of young plaice were to be taken from the Flemish Bight and other coastal areas and put down on the Dogger Bank where, it was believed, they would grow more quickly. However, this too has not so far been found practicable and two other methods of control remained. One was to fix a size limit below which it would be illegal to catch or land fish. This, it was thought, would discourage trawlers from fishing on the grounds where only small fish were to be found, but this plan also came to nothing because no agreement could be reached, so far as the plaice was concerned, as to the most suitable size limit to establish. The outbreak of war in 1914 put an end to the discussions temporarily but they were resumed after the war along quite different lines and a fourth and last method of control was suggested. This was to increase the size of the mesh of the net so as to let a larger proportion of small fish through. The difficulty here was that if the mesh were increased so as to let through a large proportion of small fish of one sort, say plaice, it would also let through too many large fish of another sort, say whiting. A great many experiments with special trawls were carried out during the twenties and in 1933 an act was passed in Great Britain fixing a minimum size of three inches for the mesh of trawls and also laying down certain size limits for various kinds of fish. In 1937 ten of the principal fishing nations, on the recommendation of the International Council, put their signature to a convention along the lines of the British act though not all of them ratified it. When the second World War broke out the regulations

were suspended but in 1943 a conference was held in London at which another draft convention was drawn up between the various allied governments, many of them in exile, embodying similar regulations for the control of fishing after the war.

Fishery research aims ultimately at the solution of several problems. There is the problem of the depletion of the stocks of fish by overfishing. For the solution of this the slow accumulation of accurate statistics is necessary. From the figures collected the total yield and the density of the stock can be watched from year to year. There is the problem of the growth rate of the fish and the size and age at which they reach maturity. It is obviously important to know these before size limits can be fixed. Then there is the problem of the age of the stock on the various grounds and at various times. All these questions must be dealt with before an estimate can be made of what is known as the optimum catch—the amount of fish which can be taken out of the sea in any area to provide a profitable industry without harming the stock.

The age of the fish can be found out by counting the rings on the scales, representing zones of summer and winter growth, or the similar rings on the ear stones. If the lengths of all the fish of one sort, say the plaice or herring, in a random sample are measured it is found that certain lengths predominate. These lengths, when linked up with measurements on the scales and ear bones, are found to distinguish groups of fish all of a certain age. All the fish in each group were hatched, in other words, in a certain year. There have, in fact, throughout the history of our fisheries been certain years distinguishable as good years, which can be traced in the population for many succeeding years by a diminishing dominance of

fish all of a certain length. There have also been bad years, years of scarcity, which can be traced in the population in later years by a scarcity or absence of fish of intermediate lengths. Although the herring and other pelagic fish are not at present in danger from overfishing, yet they, as well as all kinds of demersal fish, are subject to these unaccounatble fluctuations. The year 1904, for instance, produced an enormous brood of herring fry along the Norwegian coast. They were still traceable in the catches of 1919 by an abundance of fish fifteen years old. In the North Sea the supply of haddock was very much above the average in 1920, 1923, 1926, 1928 and 1931. What is the cause of these fluctuations? It is the business of fishery research to find out. So far no answer to the question has been found but it is at least certain that it has nothing to do with the numbers of eggs shed, for good spawning years have been, in the event, poor brood years and vice versa. Whatever the factors may be which influence survival it seems that the critical period comes when the fish is a young fry. A shortage of planktonic food, unsuitable temperatures, a shift of the current, sweeping eggs and larvae into adverse conditions, an increase in natural enemies—all these may cause high mortality among the young fish. Conversely, correct conditions may bring about a great increase in the young fish and a good brood year. This is, indeed, a side of fishery science about which as yet very little is known. The problem is, at present at any rate, quite outside the artificial control of man.

The attempts of mankind to supplement artificially the stocks of fish in the sea have so far only occasionally been successful on a limited scale. As we have seen there has been some success in transplanting young plaice

from one ground to another and so speeding up their growth but on this side of the Atlantic artificial stocks of fish have never been added on a bigger enough scale to influence the fishery very much on any part of the coast. In America, however, the eggs of the shad (*Clupaea sapidissima*), which had been collected and hatched on the Atlantic coast, were set free near the Sacramento River in California and took so well to their new surroundings that in a few years a profitable shad fishing industry grew up on the Californian coast, thus artificially created. Around our own coasts plaice have been hatched at Port Erin in the Isle of Man and at Aberdeen and set free into the sea with some success but never on a scale large enough to have any effect on the fishery. Recently, however, interesting work has been done in certain enclosed or almost enclosed lochs on the west coast of Scotland. The water in these lochs was manured in spring and early summer with nutrient salts with the result that an immense increase in plant and animal plankton took place. Plaice introduced into the lochs at the same time added to themselves two years' normal growth in the space of six months and became mature earlier than they normally would. These interesting experiments, the work of naturalists at the Millport Marine Biological Station in the Clyde, suggest the possibility of artifically increasing the production of plankton in the sea and so speeding up the growth of fish. But as the work is still going on it is best to leave the subject of the fertilization of the sea with a question mark. We can say, at any rate, that anything that we may do in this direction at present is literally a drop in the ocean, quite without any effect on the processes that go on there, for these are on a scale far beyond our powers to match.

CHAPTER IX

WHALES AND WHALING

*Whalebone and toothed whales—Blue and Fin whales—Life history of whalebone whales—Whale catchers—Blubber—Sperm whales—History of whaling—Modern pelagic whaling—*Discovery *investigations—Control of whaling.*

THE GREAT whales of the Antarctic form another marine population which is being intensively fished and which presents problems in many respects parallel to those of our fisheries. Before the war a fleet of some forty whaling factory ships, some of them of 20,000 tons or more, worked along the edge of the Antarctic pack ice every southern summer. Each ship took about 1,000 whales a season and the effects of overfishing were beginning to show themselves, not yet in any decline in the total yield nor in the density of the stock such as we see to-day on our home fishing grounds, but in an increase in the proportion of small immature whales in the catches. This was particularly evident in the years before the war in the catches of the largest and commercially most valuable whales, the Blue whales.

The whales which are hunted on a commercial scale to-day are whalebone whales. They have, instead of teeth, a row of horny fringed plates, triangular in shape, hanging down on either side from the upper jaw and no teeth in the lower jaw. With these plates they filter out of the water the plankton animals that are their food. During the eighteenth century the Sperm whale, the largest of the whales which have teeth and not whalebone plates, was also hunted by the whalers all over the world

but particularly in the Indian Ocean. Nowadays, however, the commercial value of the Sperm whale, and of the spermaceti which it carries in a cavity in its head, has greatly diminished and this whale is not taken in large numbers.

The great whalebone whales of the Antarctic are the Blue (*Balaenoptera musculus*) and the Fin whale (*B. physalus*). Another smaller whale, the Humpback (*Megaptera nodosa*), is also taken from time to time. The Blue whale is the largest animal in the world, probably the largest that has ever lived, larger even than the giant reptiles of the Mesozoic era. The cow is larger than the bull and may reach a length of nearly a hundred feet—the length of a three-car electric train. It is slate blue in colour with a flattened head and a beautiful streamlined shape, a remarkable example of parallel evolution, for the whale is a mammal, descended possibly from some creature not unlike a horse which lived in estuaries. It has returned to the sea and, as a result, has acquired again a fish-like shape, the great difference from a fish remaining in its internal anatomy which is entirely that of a mammal. The tail is horizontal and not vertical like that of a fish and the flippers conceal the five jointed fingers of the mammalian hand. From its upper jaw hang down on each side a row of black triangular horny plates, the baleen or whalebone. The Fin whale is somewhat smaller than the Blue and is nowadays taken in greater numbers. It has a more lithe and slender fish shape, is black above and white beneath and the cow reaches a length of about eighty feet. The whalebone plates are black on the left side and cream coloured on the right, a curious and mysterious asymmetry for which the reason is not known. The Humpback is a much

smaller whale. The cow reaches a length of about fifty feet. It is black and white, rather irregularly marked so that it is rare to find two Humpbacks that are exactly alike. It has a barrel shape with a slightly arched back, from which it gets its name, and enormously long flippers covered with knobs and excrescences.

All these whales belong to the class known as Rorquals which have longitudinal pleats or grooves along the under surface running from the chin to the navel. Again the exact function of these pleats is not known but they may make compression of the chest easier under water when the whale dives.

Whales spend their lives continually on the move. During the Antarctic summer they roam in herds along the edge of the pack ice where they feed on the vast shoals of a small planktonic shrimp-like creature (*Euphausia superba*) to which the Norwegian whalers give the name krill. The whales swim through the shoals of krill engulfing them in millions, forcing out the water through their whalebone plates with their huge soft inflated tongues. The tongue resembles a balloon engorged with blood, with which the whale sweeps the krill, entangled on the plates, back into the small passage of its gullet. In the Antarctic it has been established that these Rorqual whales, the largest animals on earth, feed on nothing but these small shrimps but they devour them in countless millions. In the northern hemisphere they feed on young herring, Calanus copepods or small euphausiids (*Meganyctiphanes norvegica*) rather like the southern krill.

In the southern winter, however, part of the whale population, though it is not known how large a part of it, leaves the ice edge for warmer waters off the coasts

of the southern continents. In the sub-tropical South Atlantic, Indian and South Pacific Oceans, in clear calm waters, the mating of the whalebone whales takes place. It has hardly ever been witnessed but whalers have described the gigantic copulations of the Humpback whale off the coasts of Australia and New Zealand. The two whales are said to lie side by side embracing each other with their flippers. Other accounts describe how they lash the water with their tails and with their flippers. The cow whale bears and suckles her young like any other mammal and her two mammae are in the inguinal position where the domestic cow carries hers. It is said that the cow whale shows great affection for her calf and, if it is injured or in danger, circles round it and will not forsake it. The Blue whale carries her calf for about ten months before bearing it and the Fin whale for about eleven months and, while pregnant, makes a trip to the ice edge. The whales starve when they are in the tropics for the krill does not live far from the Antarctic ice and no other diet seems to be possible. Mating takes place in June or July and the young whale is born about April or May next year when the mother, fat and with breasts full of milk after a season feeding in the south, is making her way north again. The young Blue whale is about twenty feet long when born and the young Fin whale a little smaller and, as a rule, there is only one young at a time. The calf feeds at its mother's breast for the first six or seven months of its life in the tropics and during that time has no whalebone plates but the rudimentary buds of teeth in the upper jaw. These, however, never break through, but as the time for weaning approaches they die away. Comb-like ridges appear on the upper jaw which presently, by the time the young whale is ready to feed for

itself, become horny fringed whalebone plates. In two or three years the young whale is ready to mate for the first time and is by that time about three times the size that it was at birth. A Blue whale, then, is about sixty feet long when it becomes mature and a Fin whale about fifty-five feet. Both are fully grown at six or eight years old and a whale which survives to become twenty years old is very ancient, so that the old idea that whales live for hundreds of years is certainly quite wrong. The cow Blue or Fin whale, then, has one young every two years from the time she is two years old. The intermediate months are spent carrying and suckling the young and resting before the next pregnancy. The vast majority of whales are killed before they reach an age of eight or ten years so that it is not likely that many cow whales give birth more than five times during their lives. Evidently, then, the whale population is one that recruits itself slowly and would be easily damaged beyond repair by too intensive hunting.

The chase and capture of the great whales depends upon the fact that since the whale is a mammal it must come to the surface to breathe. The Fin whale often travels about the ocean in herds of up to fifty, called schools, sometimes all of the same sex, but the Blue whale travels in smaller schools of three or four. Both, however, are found travelling alone often enough. When not being chased or disturbed they swim along just beneath the surface and, every few minutes, break surface to breathe. The nostrils are on the top of the great flat head and, just before the whale reaches the surface, a high fountain, called the spout, shoots into the air some twenty feet. This is sea water, condensed water vapour and some mucus forced out of the nostrils by the violent exhalation.

It is followed by a whistling intake of breath before the whale disappears again. It is this spout, seen afar off by the keen eyes of the masthead look-out, which betrays the whale to his pursuer. The whale catchers are small fast steamships of about 180 tons gross, with a low free-board, a flared bow and a small turning angle. A harpoon gun is mounted on a platform in the bows. The harpoon is an iron spear about four feet long, muzzle loaded into the gun and fired from it by a black powder charge. It has an explosive head which, set off by a time fuse, explodes inside the whale, breaking its back if the harpoon has struck, as it should, between the shoulder blades. When the whale has been struck he makes a sounding dive, going down very deep, though how deep is not known, possibly several hundred feet. He carries out, attached to the harpoon, a long length of line which runs up over pulleys on the mast and down into the hold. The whale may not immediately die after he has been struck but may come to the surface and fight for his life, so that an exciting half-hour or so may follow the shot during which the whale is played like a gigantic fish, the mast acting as a fishing rod. But when at last he is dead he is hauled close to the ship, his spreading tail flukes are cut off and compressed air is pumped into his belly to make the carcass float. Then he is towed back to the factory ship tail first and there stripped and cut up for the boilers.

The blubber, from which the finest whale oil comes, is a layer of crisp, fibrous white fat beneath the skin. The whale, being a mammal, is warm blooded, so that, like all other mammals, it must have some protective covering as an insulation from the cold world in which it lives. When it left the ancestral estuaries and took to the sea it

lost its hairy mammalian pelt except for a few sparse bristles on the nose and chin. It developed instead this layer of fat beneath the skin which may be as much as nine inches thick on the flank of a whale fattened after a long sojourn in the south, but only an inch or so on a whale which has been starving in the tropics. But, in addition, all the bones and tissues and all the body fluids are heavily impregnated with oil so that on board the factory every scrap of the whale's carcass is boiled down, except the whalebone plates. A large Blue whale yields about 14 to 15 tons of whale oil. Each factory ship takes about 1,500 whales in a season. In the years before the war some forty factory ships sailed from Europe alone, so that somewhere about a million tons of whale oil were brought back to Europe every year from the Antarctic.

The only toothed whale which was at one time commercially valuable is the Sperm whale. It is still taken in small numbers in the Antarctic but it gives an oil which is of less value than that of Blue and Fin whales and which does not mix with other oils so that it has to be stored separately. The Sperm whale, therefore, is not taken nowadays when other whales are available. It is an animal of weird appearance for its body seems to consist entirely of a boiler-shaped head which contains a reservoir full of an oily liquid, spermaceti, from which at one time candles were made. Under the head is a formidable snapping lower jaw like a rod armed with conical teeth, while in the upper jaw there are no teeth but only sockets into which the teeth on the lower jaw fit when the mouth is closed. The Sperm whale lives mainly in tropical waters and feeds on cuttle-fish, some of them of huge size—so large, indeed, that they have

never been taken in any net and are only known from the decaying remains found in the stomachs of these Sperm whales, which alone are swift enough to catch them. The horny beaks the cuttle-fish carry in their heads sometimes set up an irritation in the intestines of the whale so that a mucus concretion forms around them. These hard pellets, which may be the size of a baby's head, are voided into the sea and are at length washed up on the shore. There was a time when, should some lucky wanderer find these round hard concretions lying on a beach, he would have been able to sell them, so it is said, for a great price and become a millionaire at one bound, for these are pellets of ambergris, once so valuable for fixing the fragrance of perfumes. But nowadays, alas, the manufacturers of scent are no longer dependent on chance wanderers by the sea and have devised other methods of making perfumes to cheat beachcombers of their spoils and ambergris has lost its value.

In the eighteenth century American and British whalers hunted the Greenland and Biscay Right whales in northern and temperate seas and the Sperm whale in all the seas of the world. The Right whales, now almost extinct, are whalebone whales with immensely long baleen plates but no pleats running from the chin to the navel. They are known as Right whales because the old whalers distinguished two types of whales upon the grounds, the right whales which were their prey, and the wrong whales, the swifter Rorquals, which it was useless to pursue. They killed the Right whales and the Sperm whales with hand harpoons from open boats and boiled them down in pots on board ship or on the beach. At the time of the American War of Independence there

were about 700 American whaling ships on all the world's oceans, more than twice the number of all the other nations put together. The Americans and the British, whose ships from Dundee and Peterhead ranked next, are said to have worked together very agreeably even though their two countries were at war. But by the middle of the nineteenth century the great American whaling industry had completely disappeared, having, by overfishing, almost extinguished the whales which gave it life. Modern whaling dates from about 1860 when the Norwegian captain, Svend Foyn, invented the harpoon gun. This made possible the pursuit and capture of the lithe swift Rorqual whales which hitherto had been too fast for the open boats. From this time onward until quite recent years whaling became a sort of Norwegian preserve and to-day most of the personnel even of British ships is Norwegian. With the new methods the whaling began again along the coast of Norway, Iceland, the Faeroes and the Shetlands. Off the coast of Europe the whales feed in the north during the summer and move south to breeding grounds off the coasts of Portugal and North Africa and around the Azores in the winter. There were winter whaling stations on these sunny coasts also. But by the opening of the new century the same disaster had befallen the new industry as overtook the old—the whales became too scarce for profitable hunting. Whaling was carried on from shore stations in those days and the catchers were not the powerful vessels with a long steaming range that they are now. The whale is a shy beast and, when hunted too much in any neighbourhood, he moves off to another so that it seems probable that the whaling did not so much diminish the stock in those northern waters

as drive the whales away from the coast and out of range of the catchers.

When the whaling declined in the waters of the northern Atlantic the whalers began to turn their attention to the rich grounds of the Antarctic from which so many exploring expeditions had returned with reports of great herds of whales. The first whaling factory was established in South Georgia in 1902 and others followed, but many companies found it more convenient to use converted cargo ships as factories and to anchor them in harbours farther south in the South Shetlands. The sunk volcanic crater of Deception Island made a convenient anchorage and here, in the years just after the first World War, many ships, some of them very ancient, lay at anchor all the summer so long as the harbour was free from ice, their catchers hunting in the straits outside. The whales were stripped in the water alongside the ship and the carcasses cast adrift in the harbour for only the blubber was used in those days—the bad old days of southern whaling—and the wastage was appalling. To-day, nearly thirty years after, when the harbour of Deception Island is silent and empty, its black sands are strewn with whale bones, a memorial to that senseless sacrifice. Nevertheless, whaling from stations ashore or from ships anchored in bays, profitable though it may be at first, soon begins to show that it has certain disadvantages. In the first place, as we saw in the north, the whales, if relentlessly hunted, move off elsewhere. Secondly, since the whales spend their lives wandering about the oceans along certain not very well known routes, stations can only be established, or factory ships anchored, within steaming range of those migration routes. And even then they will only be of use as bases

for whaling during the limited periods when the whales are on passage through that particular area. Further, in the far south, as at Deception, whaling cannot begin until the ice clears and must cease before it closes in. Around South Georgia, not so far south, the shortening of the hours of daylight at the end of summer also limits the hunting.

From the whaling ships anchored in harbours there developed the modern pelagic system by which the entire factory, with all its tanks, machinery and personnel, is housed aboard ship. Nowadays the ships are specially built for the purpose and combine the functions of factory and tanker. Each is the mother ship of a fleet of catchers which, like the trawlers, are rapidly increasing in speed and power. Immediately before the war there were about forty European factory ships, mostly British and Norwegian but some German. Several factories were also operated by the Japanese. Some of these ships were giants of over 20,000 tons gross capable of dealing with about 1,500 whales in a season of three months. The total number of whales killed by the European factories was between forty and fifty thousand. The Japanese, who would submit to no kind of restriction, accounted for several thousand more. The question was, therefore, beginning to arise whether the slowly recruiting stock of whales could stand the strain.

It had been foreseen, however, that this question would eventually arise. In 1924 the British Colonial Office set up a Committee to investigate the habits of Antarctic whales in order that it might be possible at some time in the future to draw up regulations for the control of whaling. At that time the whaling was entirely carried on within that sector of the Antarctic

known as the Falkland Island sector, falling within a triangle based on the Falkland Islands and with its apex at the Pole. All this area is within the British Empire, administered by the Falkland Islands Government. This Committee's staff of scientists carried out patient and arduous work at sea in the Royal Research Ships *Discovery II* and *William Scoresby* whose many voyages in Antarctic seas make up the greatest oceanographical research since the voyage of the *Challenger* in 1872–76. They also worked from a laboratory ashore in South Georgia where the carcasses of about 3,000 whales were examined. The Norwegians, too, have been extremely far sighted and active in carrying out whaling research in factory ships and with their little research ship, *Norvegia*. It was indeed one of the few rays of light that shone in a darkening scene before the war when, largely as a result of this work in the south, the whaling nations signed a convention in 1937 agreeing to a number of rules for the control of whaling. They agreed, among other things, to limit the season to three months and not to work with fleets of more than seven catchers. They agreed not to take whales under a certain length which could be easily judged from the deck of a catcher nor to take cows running with calves and to use every scrap of the carcass.

Now that the war is over there has been an even greater increase in the fishing power of the whaling fleet. Aircraft reconnaissance, radar and asdic devices are all being pressed into service. Bigger and more efficient factories are being built. In spite of that there has been an increase in the total yield of only about 11% over pre-war years and there has been a decrease in the average age of Blue whales, the most valuable commercially.

An increasing number of young immature whales is being taken. Nevertheless we may hope that in the new mass attack, which is being made with all the resources of total war, upon the shy and harmless leviathan, it will be found that wise control has been exercised in time.

CHAPTER X

INSTRUMENTS AND METHODS

Aims of oceanography—The work of a research ship—Observation stations—Sounding—Water sampling—The Nansen-Pettersen bottle—The Ekman reversing bottle—Deep sea thermometers—Plankton collecting—Plankton nets—Vertical closing nets—Towed nets—Depth recording instruments—Trawling and dredging—Hints for collecting, preserving and handling animals at sea—Bottom sampling instruments.

In oceanography and in the study of fisheries the principal aim of research is to relate the plant and animal populations to their world, the sea. The general plan of operations is divided into two primary parts. The first part is concerned with the catches themselves and must involve the examination of thousands of fish, either aboard the fishing vessels or after the catches have been landed, to find out what they feed on, when and where they breed, the age of the population, the sex ratio and so on. All the fish will have to be measured and separated into groups and classes for an accurate statistical analysis of the catches. Marking experiments may be carried out to trace migrations. All this work, however, must be supplemented by the second part of the plan of operations, the attack on the problems of the sea itself. The movements of bodies of water must be traced from one area to another. The movements and cyclical changes in the dissolved salts and gases in the sea must be observed. The unravelling of the life histories of all the important living creatures, both plant and animal, their relationships to each other, their distribution and

reproduction, and all the factors—chemical, physical and biological—affecting them are not the least of the problems with which oceanographers have to deal. This can obviously only be carried out at sea and falls once more naturally into two parts, the study of the sea water, its movements and chemical and physical properties, and the study of the animal and plant life in it, whether plankton, nekton or benthos. It needs a ship specially built for the purpose and equipped with a large number of different instruments for collecting, measuring and analysing samples of sea water as well as many different kinds of nets, dredges and trawls for sampling the living population of the sea.

In order to observe and trace the great seasonal and cyclic changes which go on in the sea it is important to make repeated observations over a selected area and to repeat them at regular intervals throughout the year for as many years as possible. One of the objects for which the International Council for the Exploration of the Sea was founded was just this—the taking of regular co-ordinated repeated observations in areas of sea which would be thus kept permanently under review. The first ship to carry out a programme of regularly repeated cruises in the deep ocean was the *Michael Sars*, built in 1900 by the Norwegian Government. She took observations at regular intervals in the North Atlantic for a number of years. Since then most of the marine biological and fishery research stations in the world have, with vessels of one sort or another, carried out similar investigations over restricted areas of their local seas. But the first ship to do so on a really world-wide scale was the *Discovery II* when, in the early thirties, the growth of pelagic whaling extended the field of her research

round the whole vast area of the Southern Ocean. Certain meridians of longitude were selected, that of 78° West and that of Greenwich, and along these, at intervals throughout the year, series of observations were taken from some point north of the antarctic convergence southwards. Between these meridians more extensive surveys were carried out at approximately half-yearly or yearly intervals over wider areas, such as, for instance, the whole area of the Falkland Islands sector from the Horn on the west to the eastern margin of the Weddell Sea on the east.

The work of every research ship is based on the same fundamental twofold plan, with separate but co-ordinated physico-chemical and biological sections, whether the area to be studied is a local one, like the North Sea, or a world-wide one like the Southern Ocean.

Observations are taken at points selected beforehand when the plan of research is mapped out. At each point a series of samples of sea water is collected and temperature readings are taken at fixed depths from the surface down to the bottom. The samples are analysed by the chemists for their salt content, density, oxygen, phosphate, nitrate and silicate content and any other physical or chemical properties which it may be necessary to study. At the same time, or immediately afterwards, samples of the plankton are taken with nets of various patterns from selected depths. Or the benthos may be sampled with a dredge, or a trawl may be shot to sample the benthos and the fish that live on it.

In the *Discovery II*, when a survey of the plankton of the open ocean was in progress, a full series of observations was usually taken at night because during the hours of darkness the plankton is more abundant at the surface.

Intermediate observations, however, might also be taken during the day. The ship steamed along the route over which the observations were to be taken and stopped at night, usually a few hours after sunset, in order to take a complete series of temperature readings and water samples from the surface to near the bottom and biological collections from routine levels down to about 500 fathoms. In fair weather, with the ship maintaining a constant average speed, one may be fairly sure that the observation points, or stations as they are called, will be evenly spaced along the route, but if bad weather interferes with the programme, as it often does in southern waters, the times at which observations are taken must be adjusted. The first observation to be taken at each point must obviously be the depth of the sea, since we wish to take water samples down to as near the bottom as possible. In the old days of the *Challenger*, and even as late as the early years of the *Discovery* Committee's work, soundings had to be taken by the simple but laborious and inaccurate method of lowering a weight to the bottom on the end of a rope or, later, on a pianoforte wire. A sounding of several thousand fathoms by this method might take many hours to accomplish and, if anything went wrong, thousands of fathoms of expensive wire and hours of equally valuable time and much temper were lost. But of recent years the modern method of echo sounding has done away with this laborious process. This is not the place in which to describe the echo-sounding device, and its principles, anyhow, are well enough known. A diaphragm on the ship's bottom is electrically vibrated and the vibrations travel down to the bottom of the ocean, returning as an echo which is picked up by a receiving diaphragm and electrically

recorded. Sounding in the deepest water in the roughest weather is, by this method, only a matter of seconds. Let us suppose that the depth of the sea at our station is 3,875 metres (nearly 2,000 fathoms). We shall then need to take temperature readings and water samples from the surface to within a safe distance of that depth. Now the plankton population, living as it does mainly within the surface 100 metres (50 fathoms), is more intimately related to the chemical and physical properties of the water within that layer than to those of the layers below. Conditions also in this upper layer are more variable than in the more uniform and stable layers below about 100 fathoms. In order to obtain our world-wide picture of the ocean and the movements of water masses we must take observations down to the bottom, for such a picture will be the result of the co-ordinated analyses of thousands of samples of sea water. Temperature readings and water samples are therefore taken at frequent intervals down to about 200 metres (100 fathoms), but at much wider intervals in the more stable deeper layers.

For the shallower observations down to about 200 metres a type of instrument is used which is rapidly lowered to the required depth, collects a water sample at that depth and records a temperature and is then hauled swiftly up again and emptied of its water sample. The temperature is read and the instrument immediately and quickly lowered to the next depth. This is the Nansen-Pettersen type of water bottle. It consists essentially of a metal cylinder, made of bright metal on the outside so as to reduce the absorption of radiant heat, and insulated on the inside by a number of concentric jackets, so that the sample, once collected, does not lose heat to the surrounding water or gain heat from it. The

cylinder is carried in a rectangular metal frame and the disc-shaped plates that close it at the top and bottom are held open by springs until the instrument reaches the depth from which the sample is to be collected. A thermometer carried in a shaft at the top of the bottle records the temperature of the sample.

Sampling instruments are lowered into the water attached to steel wires running off winch drums. To each winch drum a revolution counter is attached so that the depth to which the instrument descends can be read off directly from the amount of wire which has been paid out. The wires run up over davits on the ship's side, passing over a system of sprung pulleys, known as accumulators, which neutralize and damp down the uneven strains caused by the constant rolling of the ship. In heavy weather the violent jerking movements of the ship would certainly break even the strongest wires.

The Nansen-Pettersen bottle is attached to the end of its wire and lowered to the required depth as indicated by the revolution counter. A small conical weight, known as a messenger, is then clipped on to the wire and, sliding down it, strikes a catch on the head shaft of the frame of the bottle. This releases the springs that hold open the top and bottom plates of the cylinder so that they snap to and close the bottle. A sample of water at that depth is thus trapped. The thermometer takes up the temperature of the sample while the bottle is being hauled to the surface. When the instrument has been brought up on deck the temperature reading is at once taken and the water is run out from the cylinder into a stoppered glass bottle, labelled and put aside for analysis.

The Nansen-Pettersen bottle can be used for all the samples which are taken from the shallower depths. It

can be lowered quickly and hauled in quickly and each observation occupies only a few minutes but, for a number of practical reasons, it cannot be used for the greater depths. In the first place it would take too long to lower the bottle to each of the depths below 200 metres in turn and haul it in again and, in the second place, the sample would have time to acquire a different temperature by the time it reached the surface. Further, the temperature of the sample is different at the great depth from which it is collected from its temperature when it reaches the surface because of the difference of hydrostatic pressure between the two levels. We must therefore use for these greater depths some kind of thermometer which will permanently register the temperature at the level from which the sample is taken.

For all readings and samples below about 400 metres, therefore, a different type of bottle is used, known as the Ekman reversing bottle. A string of these instruments is attached to the same wire so arranged that when all the wire has been paid out the bottles stand at the levels from which the samples are to be taken.

Each Ekman bottle consists, like the Nansen-Pettersen type, of an insulated metal cylinder set in a rectangular frame which can be clamped laterally to the wire by a screw clamp. Each cylinder is weighted at one end and pivots upon a central axis. When the bottle is open the weighted end of the cylinder is upwards, held in place by a spring catch. The disc plates which form the top and bottom of the cylinder are held apart by rods which ride upon central cams around the pivot of the cylinder. When the instrument has reached the proper level a messenger is sent down the wire, strikes a lever on top of the frame and releases the catch holding the weighted

head of the cylinder. The cylinder, overbalanced by its weighted head, turns over and clips into position the other way up with the weighted end downwards. As it turns over the rods ride over their cams and, helped by springs inside the bottle, bring down the plates on the top and bottom, closing the cylinder and trapping a sample of water in the same way as in the Nansen-Pettersen pattern. When the topmost instrument in the string, or flight, swings over it releases another messenger attached beneath it which travels down the wire and strikes the bottle below. This in turn releases a third messenger and so on. Thus the whole flight of bottles is closed by sending down a single messenger from above.

The thermometers used with the Ekman bottle are of a different type from the ordinary pattern used with the Nansen-Pettersen bottle. Small temperature differences at great depths may profoundly affect the density of the water so that readings may need to be accurate to within one hundredth of a degree centigrade. For this reason two thermometers are carried on each bottle so that one may act as a check on the other. Further, the length of the mercury thread in a thermometer is quite considerably affected at great depths by the hydrostatic pressure acting on the bulb. Unless, therefore, a thermometer is protected against pressure it reads inaccurately. Accordingly a deep sea thermometer is enclosed in a stout glass tube partially evacuated except for the portion surrounding the mercury reservoir. This contains a mercury jacket which acts as a heat conductor between the bulb of the thermometer and the surrounding water. Another point is that a thermometer of the normal pattern takes up its temperature reading but does not hold it unless there is some device to enable it to do so. A normal

thermometer lowered to 3,000 metres would show quite a different temperature from the true one by the time it reached the surface. The thermometer used with the Ekman bottle, therefore, has a thread curled into an S-shaped bend or into a loop and constricted above the bulb, or it may be provided with a short blind branch. There is an enlargement at the other, upper end of the capillary and the mercury thread fills the whole of the capillary and part of this upper enlargement as well. The amount of mercury in the swollen upper end depends on the temperature. The thermometer is lowered on the Ekman bottle with the reservoir downwards and takes up the temperature at the level of the reading in that position. When the messenger strikes and the bottle cylinder turns over, the thermometers turn over with it. The mercury thread breaks at the constriction within the loop and the mercury in the stem runs back into the enlargement at the other end of the capillary. The temperature is read off on a scale which is graduated for the reversed inverted position. As a check against the temperature at the time of reading a small auxiliary thermometer of the ordinary type is enclosed with the constricted one in the protective glass tube. An unprotected thermometer may be used alongside the protected one. The protected one then reads the true temperature at the depth of the sample while the other has an added error which is due to pressure. The amount of this error is known for different pressures and, by noting the difference between the two thermometers, it is possible to tell exactly at what depth the instrument was standing when the temperature was recorded, for it is obvious that a length of several thousand feet of wire hanging in the water from a ship, which can never

remain absolutely stationary when hove to, will never be truly vertical and will often be far from it. Even a small slope on the wire away from the vertical will make a large error in the levels at which the instruments, especially the lower ones, really stand. When the bottle comes up to the surface the cylinder is turned over by hand to open the bottle and the mercury threads of the thermometers join up once more, becoming continuous with the mercury in the bulbs.

These are the instruments used many hundreds of times during a survey of the open ocean. At the same time samples of the plankton are collected with nets of varying fineness. The whole aim of this kind of work at sea is to make the observations as nearly comparable as possible. That is why repeated observations are taken at the same place at fixed intervals of time. That is why temperatures, water samples and biological collections are taken from the same levels at station after station. So that for collecting samples of the plankton also we must always use nets of a standard size and pattern, made of material of standard mesh. Further we try, as far as possible, to fish through columns of water of the same standard dimensions.

The nets used for collecting plankton may be of many sizes and be made with meshes of many degrees of fineness or coarseness according to the kind of catch required. The nets used for catching diatoms and nannoplankton are made of fine silk with approximately 200 threads to the inch. Somewhat coarser nets are used for catching microplankton and the smaller animals of the macroplankton. These are made of two kinds of silk with 40 and 70 threads to the inch. Still coarser nets, made of canvas with about 12 threads to the inch, are

used for catching macroplankton. But all these, no matter what their size or mesh, are built on the same basic pattern. A conical bag of netting is attached to a circular metal ring, which forms the mouth, and at the apical end of the cone is another ring, very much narrower, on to which is screwed a small metal bucket for collecting the catch. The small fine silk nets used for diatoms have a mouth 50 cms. in diameter. The coarser silk nets for collecting microplankton have a ring 70 cms. in diameter, while the canvas nets most frequently used for macroplankton have a mouth one metre in diameter, but others of larger size are often used, the largest having a ring 4½ metres (about 15 feet) across—the largest plankton net ever used. Only the small 50 cms. and 70 cms. nets, however, are used for repeated routine vertical hauls, since the larger types are too cumbersome to use for this work and would not take a big enough catch in a limited vertical column of water to make their use worth while.

The small diatom net is only used in the upper 50 metres and is hauled from that depth open to the surface since it is only in this surface layer that the diatoms exist in significant amounts. The 70 cms. silk net, however, is hauled through standard layers of water at various levels between 1,000 metres and the surface. At the top of each layer the net is closed and hauled swiftly to the surface, emptied of its catch, lowered open to the depth at which it had closed and hauled through the next layer above and so on. The thickness of the layers may be varied, of course, according to the kind of information that is required.

The wire to which the nets are attached for hauling vertically runs off a winch drum, to which a revolution

counter is connected, and over a davit with accumulators just as do the wires which carry the water bottles. Three bridles, made of wire for the diatom net and of metal for the larger 70 cms. net, connect the ring of the net to a spring trip mechanism on the end of the wire. A rope girdle, called the throttling band, encircling the net around its middle, is also connected to the trip mechanism. The net is lowered open to the depth from which it is to be hauled, say 1,000 metres. It is then slowly hauled upward at a speed of one metre per second. As it approaches the depth at which it is to be closed, say 750 metres, a messenger is sent down the wire, timed to strike the trip mechanism at that depth. The messenger depresses a catch so that the bridles carrying the net and the mouth of the net fall away, leaving the net hanging from the trip mechanism by the rope throttling band which constricts the net about its middle and closes it. It is seldom that the net closes exactly at the depth required but the error is usually small enough to be ignored in work of this sort into which enter so many other errors that can neither be measured nor avoided, such, for instance, as a slant on the wires which may carry the net away from the depth shown on the revolution counter, the possibility of the net catching some animals on the way out or of some avoiding the net by swimming away from it, or variation in the size of the catch caused by shoaling of the plankton and so on.

These vertical hauls, however, do not take very large catches. Even in the richest waters in the height of summer the largest catch with a vertical net seldom fills a half-pound jar. If diatoms are very abundant they clog the net and make the catch bulk largely but it is the zooplankton that these nets are intended to catch.

Furthermore only the small nets can be used since the larger ones are too cumbersome to handle. Accordingly, in order to obtain larger samples of the plankton, though from less evenly standardized layers, nets must be towed for some distance through the water either obliquely or horizontally. This is done over the stern of the ship under weigh at slow speed steaming into the wind. Flights of nets of convenient size may be attached serially to a stout trawling wire running off a winch over fair leads on the poop rail. Each net is closed by a messenger released from the one above it, the top one of the flight by a messenger clipped on to the trawling wire from the deck. Each messenger strikes the trip mechanism of the net and releases the ring so that the net is held by the throttling band about its middle, at the same time setting free a messenger which slides down the wire to the net below. In this way flights of four, six or eight nets, attached at suitable intervals along the wire, can be towed together.

The exact depths between which nets fish when they are towed and closed in this manner vary greatly. A length of wire is paid out over the stern of the ship equal to twice the depth from which it is intended to begin hauling the lowest net, but the actual depth to which the net sinks depends on the speed of the ship and the slope of the wire as it enters the water. It also depends on the size and length of the wire and the number and size of the nets attached to it. The nearest approximation to the correct depth is obtained if the wire enters the water at an angle of 45° and the speed of the ship must be varied to keep that angle constant. Small variations in the angle of the wire make a great difference to the depth of the net and small alterations in the speed of the ship

make a great difference to the angle of the wire. It is usual, however, to attach to the wire near the net some kind of instrument for measuring the exact depth to which the net descends. When nets are towed open to the surface through shallow depths a Kelvin tube is sometimes used, lashed to a rod near the net or to a streamlined lead on the end of the wire. It is a simple device familiar to every sailor. It consists of a narrow glass tube about 18 inches long, lined on the inside by a coating of red silver chromate. Hydrostatic pressure forces the water into the tube to a distance which depends on the depth to which the tube has descended, dissolving away the red lining along a portion of the tube. The length of the colourless portion of the tube is compared with a measured scale to give a reading of the depth. This, however, is only a record of the greatest depth reached by the net. It gives no indication of the levels between which the net has fished nor does it give accurate readings for depths greater than about 75 fathoms. For greater depths than this two reversing and constricted thermometers may be used, one protected and one unprotected, held in a rectangular frame attached to the wire near the lowest net and reversed by a messenger, but, again, this is only a single reading. It records only the greatest depth reached by the net. A much more satisfactory instrument is the Budenburg depth gauge of a special modified pattern which traces a graph of the movements of the nets under water. It is attached to the end of the towing wire and consists of a U-shaped hollow pressure tube encased in a heavy cast iron water-tight cylinder. A small hole in the bottom of the cylinder leads into the tube. The U of the tube expands under the influence of hydrostatic pressure

exactly as does a steam gauge tube. One arm of the tube is fixed but the other moves a pen which writes on a revolving paper disc propelled by clockwork. As the gauge descends the pen arm moves away from the centre of the disc and makes a sloping trace on the paper. As the nets are hauled slowly in, the pen arm begins to approach the centre again and, as each net closes, the slight jerk of the wire is recorded by the pen. The distance of the trace from the centre of the disc is then a measure of the depth of the instrument at any particular moment during the haul and a complete graph of the path of the instrument under water is recorded.

These, very briefly, are the kinds of observations which were made at many hundreds of stations worked by the *Discovery II.* They differ little from those worked by other research ships which carry out plankton research in the open ocean except that they were, perhaps, on a rather larger scale. The water samples, when collected, were put aside in clean stoppered glass bottles for analysis in the laboratory. The samples of plankton were emptied out of the buckets of the nets and pickled in 10 per cent. formalin in glass screw-topped preserving jars of suitable sizes. They ranged in size from small half pound jars to large seven pound ones. Every sample was carefully labelled with the serial number of the station, the date, the type of net in which it was taken and the depths through which the nets fished. In the laboratory, eventually, every sample must be sorted, every animal identified and recorded in a log, though this, with such a vast accumulation of material, must inevitably take years to complete.

As may be imagined plankton work of this sort is unspectacular and wearisome. It is, in fact, the careful

routine collection of statistics. It seems, to the layman, to have no immediately visible result and no immediately ascertainable goal. Spectators soon tire of watching the scientists endlessly repeating the same routine over and over again and it is not long before no one, whose duty does not compel his presence on deck, attends these nightly ceremonies. The nets always bring in what appears to be the same uninspiring harvest of almost invisible seed-like objects which, to the uninitiated, seem to be exactly the same from whatever part of the wide ocean they are taken. It is not altogether surprising, perhaps, that many of the crew should come to the conclusion that scientists are a little mad.

In the investigation of fishing grounds routine plankton work such as this must be supplemented by collections of the benthos, on which the fish feed, and by samples of the bottom on which the benthos lives. For this purpose dredges and trawls of various patterns are used. Then, indeed, the interest of all the ship's company revives and the activities of the scientists become comprehensible as the mass of living creatures is emptied out upon the deck, the urchins with their myriad spines, the brittle stars shedding their arms, the feebly groping feather stars, the starfish with their slow deliberate movements, the frantically wriggling bristle worms and the formless, apparently lifeless creatures that open out into flower-like beauty when placed in clean cold water.

A small otter trawl may be used for this sort of work but it is unsatisfactory to handle if the ship is not fitted with forward trawling gallows. The handiest and most useful instrument for sampling the benthos is the naturalist's dredge. It consists of a bag of stout netting attached to a rectangular steel frame, usually 4 feet long

and 1 foot in breadth. The frame has a bevelled edge about 3 inches wide which digs into the bottom and double bars, attached to the frame on each side, form arms by means of which the dredge is made fast to the towing wire. A stout canvas apron above and below the bag of the netting protects it from the wear and tear of the rough bottoms over which the dredge is hauled. The strain on such an apparatus as this, when it is hauled over rocky and stony grounds, is very great and few rope dredges last long—the rope bag becomes torn and the steel frame bent and twisted.

A small conical dredge is sometimes used to bring up samples of the soft bottom and the animals that live in sand, mud or small stones. It is simply a conical canvas bag with a mouth reinforced by a circular steel rim which bites into the bottom like a shovel. Another instrument used for bringing up samples of the bottom is the Pettersen grab which consists of two steel jaws which bite out a measured area of the bottom. It can be used for making quantitative estimates of the benthos population in soft grounds.

When dredging it is the usual practice to pay out a length of towing wire equal to three times the depth of the water where it is intended to dredge. The ship then steams slowly ahead into the wind with a speed of a knot or so. It is easy enough to judge when the dredge is on the bottom by placing the hand on the wire and feeling the quivering strain upon it as the dredge drags over the bottom. When the catch comes in it is emptied upon the deck and carefully sorted. All animals must be placed in clean water at once, for one of the elementary rules of collecting is that living creatures must never be allowed to dry up. Nor must they be handled. Marine animals

have a violent and not unnatural distaste for hot human hands. In fact many animals react violently to handling. Brittle stars and feather stars immediately snap off their arms. Sea-cucumbers eviscerate themselves and leave a sticky stringy mess of intestines behind. A great many beautiful bristle worms slough off the plates, the elytra, which they carry on their backs. No attempt must be made to separate animals which are found adhering to one another in close communities. Most of the animals will be in a state of shock from their rough treatment in the dredge and from their sudden exposure to air. All polyps will be withdrawn. Worms will be shrunken and motionless and withdrawn into their tubes, if they have them. Molluscs will be retracted into their shells with their opercula, if they have them, tightly closing the entrance. But in clean cold water they all soon revive. Too many animals should not be placed in the same basin nor should the water be allowed to become foul, but if left overnight in a cool place the polyps will open again, the worms revive and stretch themselves out, the tube-living ones putting forth once more their feathery crowns. The molluscs will glide about seeking new and more comfortable situations. When all the animals are fully expanded again a few crystals of menthol or chloral hydrate are sprinkled on top of the water. This has an anaesthetic effect. It relaxes the muscles so that polyps cannot withdraw themselves. Tube-living worms remain with their crowns of tentacles permanently unfurled, while molluscs remain extended and motionless. When all movement has ceased, after some hours, the animals may be fixed in this distended condition in 10 per cent. formalin. Some, however, require rather special treatment. For instance delicate worms and eel larvae

(Leptocephali) are best stretched out on blotting paper moistened with formalin and then gently stroked with a camel's hair brush until they are well extended. Every animal should, as far as possible, be placed in a separate glass jar or tube and well covered by liquid so that there is no risk of any part of it drying up. Every tube or jar should be carefully labelled at once—and this is another of the collector's golden rules, that every specimen must be labelled clearly and at once. The label should carry the serial number of the station at which the specimen was taken, the date, the type of dredge used, the depth of the water where the dredge was used and the order, family or genus to which the specimen belongs. Somewhere, either on a label or in a separate log, to which the label carries a reference, there should be notes on the colours of the specimen, since in formalin these soon fade, on the other animals found in association with it and indeed on any facts about the specimen which appear to be at all worthy of note. Specimens preserved in tubes should not be corked for corks are never air tight. The tubes should be closed with wads of cotton wool wrapped in tissue paper. As many tubes as possible containing animals of the same type should then be placed together, packed in cotton wool, in screw-topped jars of suitable size full of formalin.

Crustacea and other animals with hard external parts, such as echinoderms, are best changed into 70 per cent. alcohol after preliminary fixation in formalin. Particular care should be taken to see that the formalin is neutral for if it is at all acid calcareous animals, such as echinoderms and false corals, will be damaged by solution. Accordingly a bag of ordinary borax should be kept hanging in the tank in which the formalin is stored. For

many animals with delicate tissues requiring special examination or special treatment in the laboratory a mixture of formalin and picric acid is used (Bouin's solution) which has an excellent hardening effect. After a day or two it should be replaced by successive changes of 70 per cent. alcohol. It is, in fact, a good rule to change the liquid in all tubes after the specimens have occupied them for a day or so. The original fixative, stained with colouring matter which has soaked out of the specimen, should be renewed until it remains clear.

As little as possible of a sample brought up with a dredge should be thrown away. When all the visible living creatures have been sorted out the residue of sand or mud, or a convenient fraction of it, should be preserved in a screw-topped jar in alcohol and carefully labelled. For the residue will undoubtedly contain Foraminifera and other microscopic creatures which will at a later date require the attention of an expert.

All these simple rules for collecting, labelling and preserving specimens are of immense importance and make a very great difference to the value of the collections when they finally reach the experts who will identify them. For the identification of marine, and indeed all other, animals is an expert's job. Practice and experience enable the collector to identify some of his catch on the spot, but for systematic cataloguing and classification the specimens, labelled and preserved as carefully as possible, must be submitted to experts who often work in the great museums where they can compare the collections with those of other expeditions.

The various instruments for taking cores of the soft deep-sea deposits may be used from time to time by any

research vessel but they do not form part of the equipment for taking repeated routine observations. Samples of the deep-sea deposits are of great academic interest and importance but a ship engaged on a full programme of fishery research seldom has time for such work as this which belongs properly to the province of pure exploration. A sample of ooze from a depth of several thousand fathoms may take hours to obtain and the operation is a hazardous one for it may involve the loss of thousands of fathoms of wire and much valuable time. Nevertheless, on several occasions, as opportunity arose, cores of the bottom were taken by the *Discovery II* in deep water.

For shallower depths, down to about 250 fathoms, the instrument used consists of a conical lead weighing 28 lbs. At its lower end is a short metal cylinder about 7 inches long. The core, which can only be a short one, is driven into this cylinder by the weight of the instrument as it strikes the bottom. A pair of butterfly valves at the opening of the cylinder prevent the core from being washed out while the apparatus is being hauled to the surface and a series of holes at the upper end allows the water to escape as the core is forced into the cylinder.

At greater depths than this a heavier weight is necessary but, because of the lightness of the pianoforte wire which must be used, the weights must be detachable since otherwise the instrument could not be hauled up but would break the wire. The type of instrument used for deep bottom cores is known as the Baillie rod. The instrument itself weighs only 10 lbs. and works on the same principle as the other type but it is used with heavy cast iron sinkers which become detached when the instrument strikes the bottom. Another type of core sampler used for deep water is the Ekman-Nansen

pattern which is not essentially different from the Baillie rod. It has a detachable weight but is about five feet long and has a thick glass tube within it into which the bottom core is forced. This can be removed and the core examined in one piece.

There are many other instruments used in oceanographical research but there is no space to describe them here—current meters, underwater photometers, continuous plankton recorders. All are becoming more complicated and refined as experience of their use accumulates. The technique of the science of the sea has made great strides since the days of the *Challenger*. When she made her pioneering voyage round the world in 1872–6 there were no steel wires and ordinary Manila rope was used for all purposes. Accumulators were made of stout rubber bands. Nets were always towed open to the surface for the closing mechanism had not been invented and it was not possible to make quantitative hauls through standard comparable layers of water. There was no way of judging the depth of any net or instrument save by the amount of rope paid out. The ship herself was a sailing ship which drifted with the wind when stopped so that the instruments and nets must have often trailed to leeward. Nevertheless the great men who were her scientists, Sir Wyville Thomson, Sir John Murray and Professor H. N. Moseley, laid the foundations of the modern science of the sea with its refined and complicated technique. We may be proud of their achievements and confident that they have worthy successors.

No inhabitant of these misty islands lives far from the sea, and for this reason, perhaps, the sea is in our blood. Only a seafaring people, with a maritime tradition, could

in time of war so quickly and so easily have turned the boys from its mean streets into sailors. And now, in time of peace, we leave our teeming cities every summer to pay homage, after our own manner, to the sea, as though in acknowledgement of the many blessings that we owe to it. We refresh our spirits with its changeful beauty and eternal mystery. But few of us, perhaps, realize as we do so that we are in fact playing on the confines of a vast and multitudinous world where even now, with our complicated instruments, we can only grope feebly for the truth. Much of that world remains hidden. If these pages have helped to make clear some of its mysteries they will have served their purpose.

BIBLIOGRAPHY

DALY. R. A.: *The Floor of the Ocean.* (1942) Deals with the structure of the true floor of the ocean, with an account of submarine canyons and the author's glacial control theory of coral reef formation. Easy to read for those who require more detailed information than is given here.

DAVIS, W. M.: *The Coral Reef Problem.* (American Geographical Society, Spec. Pub. 9, p. 596. 1928.) A full and detailed exposition, written before the work of the Great Barrier Reef Expedition (1928–9) was published. Not for the general reader.

DEACON, G. E. R.: 'A General Account of the Hydrology of the Southern Ocean.' (*Discovery Reports*, Vol. VII, pp. 171–238. Cambridge University Press. 1933.)

—— 'Ocean Waves and Swell.' (*Occasional Papers of the Challenger Society*, No. 1. London, 1946.)

—— 'Water Circulation and the Surface Boundaries in the Oceans.' (*Quarterly Journal. Royal Meteorological Society*, Vol. LXXI, Nos. 307–8, January–April. London, 1945.)

FLATTELY, F. W., and WALTON, C. L.: *The Biology of the Sea Shore.* (1922) Standard work for the general reader.

FOWLER, G. HERBERT, and ALLEN, E. J.: *Science of the Sea.* (1928) Written for yachtsmen and sailors interested in the subject, describing oceanographical instruments and methods of collecting and preserving. Highly recommended for the general reader.

GRAHAM, MICHAEL: *The Fish Gate.* (1943) For the general reader.

HERDMAN, W. A.: *The Founders of Oceanography and their Work.* (1923) Highly recommended for the general reader.

HARVEY, H. W.: *Biological Chemistry and Physics of Sea Water.* (1928) Standard textbook on the subject.

—— *Recent Advances in the Chemistry and Biology of Sea Water.* (1945)

JENKINS, J. TRAVIS: *The Sea Fisheries.* (1920) Standard work. Deals with the life histories of the principal sea fishes of the northern fisheries and the position of the fishing industry prior to the war of 1914–18.

—— *The Fishes of the British Isles.* (1925) A useful pocket guide.

JOHNSTONE, JAMES: *Conditions of Life in the Sea.* (1908) Standard work, though in some respects now somewhat out of date.

—— *An Introduction to Oceanography with Special Reference to Geography and Geophysics.* (1923)

—— *A Study of the Oceans.* (1930)

KEMP, S. W.: 'Oceanography and the Fluctuations in the Abundance of Marine Animals.' (*British Association Reports,* Section D, 1938.)

KEMP, S. W., HARDY, A. C., and MACKINTOSH, N. A.: '*Discovery* Investigations, Objects, Equipment and Methods.' (*Discovery Reports,* Vol. I, pp. 141–232. Cambridge University Press, 1929.)

MACKINTOSH, N. A.: 'The Natural History of Whalebone Whales.' (*Biological Reviews,* Vol. 21, pp. 60–74. 1946.)

—— 'Southern Stocks of Whalebone Whales.' (*Discovery Reports,* Vol. XXII, pp. 197–300. Cambridge University Press, 1942.)

MACKINTOSH, N. A., and WHEELER, J. F. G.: 'Southern Blue and Fin Whales.' (*Discovery Reports,* Vol. I, pp. 1–137. Cambridge University Press. 1929.)

MACMAHON, MAGRI A. F.: *Fishlore.* (1946) An excellent little book for the general reader, mainly concerned with fresh water fishes but with a section on sea fishes as well.

MEEK, ALEXANDER: *The Migrations of Fish.* (1916) Standard work: for the general reader.

MURRAY, SIR JOHN, and HJORT, JOHAN: *The Depths of the Ocean.* (1912) Comprehensive standard work based on the cruises of the Norwegian ship, *Michael Sars.* Recommended for the general reader who wants a comprehensive review of the subject. Now slightly out of date in some respects.

MURRAY, SIR JOHN, and RENARD, A. F.: 'Report on Deep Sea Deposits, based on the specimens collected during the voyage of H.M.S. *Challenger* in the years 1872–76.' (*Challenger Reports,* His Majesty's Stationery Office, p. 525. 1891.)

NATIONAL RESEARCH COUNCIL (various authors): 'The Domain of the Oceanography.' 'Bottom of the Ocean.' 'Properties of Sea Water.' 'Movements of Sea Water.' 'Oceanographic Instruments.' 'Relations of Oceanography to Other Sciences.' *Physics of the Earth—V, Oceanography,* (*Bulletin of the U.S. National Research Council,* No. 85 p. 561. June 1932.)

RUSSELL, E. S.: *The Overfishing Problem.* (1942) A series of lectures by the head of the Fishery Research Laboratory, Lowestoft, on the problems connected with the stocks of fish in the sea. Highly recommended for the general reader.

RUSSELL, F. S., and YONGE, C. M.: *The Seas, Our Knowledge of Life in the Sea and How it is Gained.* (1944) Surprisingly comprehensive and charmingly written account of our knowledge of life in the sea for the elementary reader. Illustrated. Highly recommended.

STANLEY GARDINER, J.: *Coral Reefs and Atolls.* (1931) A collection of lectures delivered to the Lowell Institute, Boston, in February 1930. A general account of the formation and natural history of coral reefs and atolls based largely on the author's own observations in the Indian Ocean.

STEERS, J. A.: *The Unstable Earth, Some Recent Views on Geomorphology.* (1945) An account of the modern theories of the structure of the earth's crust, the geology of the ocean basins, the formation of continents (Drift theories, &c.), formation of coral reefs, submarine canyons. Not easy to read.

STEVENSON, T. A.: 'Coral Reefs.' (*Endeavour*, Vol. V. No. 19. July 1945.)

SVERDRUP, H. U., JOHNSON, M. W., and FLEMING, R. W.: *The Oceans, Their Physics, Chemistry and General Biology.* (1942) A voluminous and comprehensive American standard text-book of oceanography. Not for the general reader.

WILSON, D. P.: *Life of the Shore and Shallow Sea.* (1935) Popular account of the subject illustrated by splendid photographs taken by the author, who is one of the most expert photographers of marine life in the world.

YONGE, C. M.: *British Marine Life.* (1944) Charmingly written and illustrated. Deals mainly with the seashore.

—— 'Observations on the Biology of Coral Reefs.' (*Proceedings of the Sixth Pacific Scientific Congress, California, 1939.* Vol. III, pp. 605–13. 1940.)

—— *A Year on the Great Barrier Reef.* (1930) A popular account of the work of the Great Barrier Reef Expedition (1928–9) by its leader. Highly recommended for the general reader.

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